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THESIS

SELF-DEFENSE OF LARGE AIRCRAFT

by

Zeki Yildirim

March 2008

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13. ABSTRACT (maximum 200 words)

Large aircraft are important assets in the military, as well as in civilian aviation. Today, the threat is not only in the battlespace but is also emerging and distributed throughout all the places where large aircraft operate. The threat has expanded due to new developments in advancing missile technology. This study is meant to be a comprehensive guide for non-technical aircrew and an introduction for technical personnel by defining threat technologies, detection systems and systems to counter today's surface-to-air missile technologies and possible future developments. Countermeasures are expressed both scientifically and operationally with examples from the current market. The emerging threats of man-portable air defense systems (MANPADs) and infrared technology are also reviewed. The hardness of flying platforms and survivability issues are explained, including the latest examples from operations in Iraq.

The goal of this study is to assist in the design or modernization of a large aircraft with equipment according to new demands both in the battlespace and in normal civilian operations.

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SELF-DEFENSE OF LARGE AIRCRAFT

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Submitted in partial fulfillment of the
requirements for the degree of

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

As information propagates from one place to another at the speed of light, the race between the air defense systems and the aircraft self-protection systems becomes more challenging. In this race, new disciplines and study areas arise. Technological developments lead to smaller and more powerful electronics components. Moreover, the proliferation of surface-to-air missiles makes it difficult to predict where or when those threats will be encountered. This circumstance increases the demand to protect the large aircraft, not only in the military but also in civilian aviation. This study is a comprehensive guide to the self-defense of large aircraft. It describes the threats and the technology behind it, explains the susceptibilities of the large aircraft, analyzes different methods of detecting the threat according to various technologies, and tries to find an integrated solution to defeat the threat. If the aircraft is hit, then it finds approaches to increase survivability. Therefore, it brings together the operational and scientific areas for not only aircrew and maintenance personnel but also technical personnel so that they may understand the systematic chain of events from detecting the threat until the aircraft survives or is killed.

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DISCLAIMER

All the calculations are on generic data and do not necessarily demonstrate real values.

The views in this thesis are those of the author and do not reflect the official policy or position of the Turkish Republic, the Turkish Armed Forces, or the Turkish Air Force.

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I. INTRODUCTION

A. BACKGROUND

Large aircraft are an essential part of military and civilian aviation. They are employed in different missions such as transportation, aerial delivery, bombing, refueling, and early airborne warning. Since each of these strategic missions directly or indirectly supports military operations, their absence has a significant impact on the large scale of battle. The importance of large aircraft can be appreciated most when they are lost. Their loss can also have considerable psychological effects on friendly forces and sensational ones on adversary forces. Therefore, they must be protected against all threats. In this thesis, the main objective is to describe the threats and the best solutions to counter them, familiarizing non-technical personnel, namely aircrews, with the technology behind the guidance and sensor systems that are in use today. In addition, potential future developments are reviewed. Although this thesis covers large aircraft, this subject is valid for every kind of air vehicle. The author matched both technology and practical application in the thesis.

B. AREA OF RESEARCH

In this study, different types of threat technologies are researched by trying to find common solutions for different types of threats in different environments, ranging from low-threat to high-threat, to protect the large aircraft.

C. MAJOR RESEARCH QUESTIONS

1. Major Question

How does a large, slow-flying aircraft survive in a battlespace threatened by missiles throughout the entire mission profile?

2. Subsidiary Questions

- What are the threats for aircraft and their technology?
- What are the susceptibilities of large aircraft?
- How can a threat be detected?
- How can a threat be countered?
- What kind of countermeasures are there in this area?
- What happens when a missile hits an aircraft?
- What will be the technology of the future?
- Is it worth equipping large aircraft with countermeasures?

D. LITERATURE REVIEW

There have been a significant number of studies in electronic warfare (EW) and defense technologies. As time goes on, new conflicts and wars break out, causing more articles and books to be written about the specific areas.

In *The Infrared and Electro-optical Systems Handbook*[1] and the radar books, the technology is described separately. New books in this area do not cover some other aspects or “why” questions.

This study fills the gaps in how to equip large aircraft to address all possible guided missiles. Therefore, it does not necessarily explain all kinds of missiles or all kinds of EW technologies.

E. IMPORTANCE AND THE BENEFITS OF THE STUDY

The past studies in this particular area do not address and show complete self-defense of large aircraft against surface-to-air missiles (SAMs). This study is meant to fill the gap by bringing together all the studies related to this particular area. It includes both current and possible future threats and solutions.

[1] J. S. Accetta and David L. Shumaker, *The Infrared and Electro-Optical Systems Handbook* (Ann Arbor, MI; Bellingham, WA: Infrared Information Analysis Center; SPIE Optical Engineering Press, 1993).

F. ORGANIZATION OF THE THESIS

This thesis is composed of seven chapters. Chapter I presents an overview to the thesis. The thesis has continuity, as it is visualized in Figure 1; it begins with Chapter I, which is an overview and introduction. Chapter II describes the characteristics, capabilities, and technology of the threat. Chapter III puts forward the vulnerabilities of large aircraft. To counter a threat, first, it should be detected and identified clearly; therefore, Chapter IV describes detection of threats. Chapter V reviews solutions to counter different kinds of threats. Chapter VI argues how a large aircraft can survive when struck by a missile. Chapter VII is the conclusion.

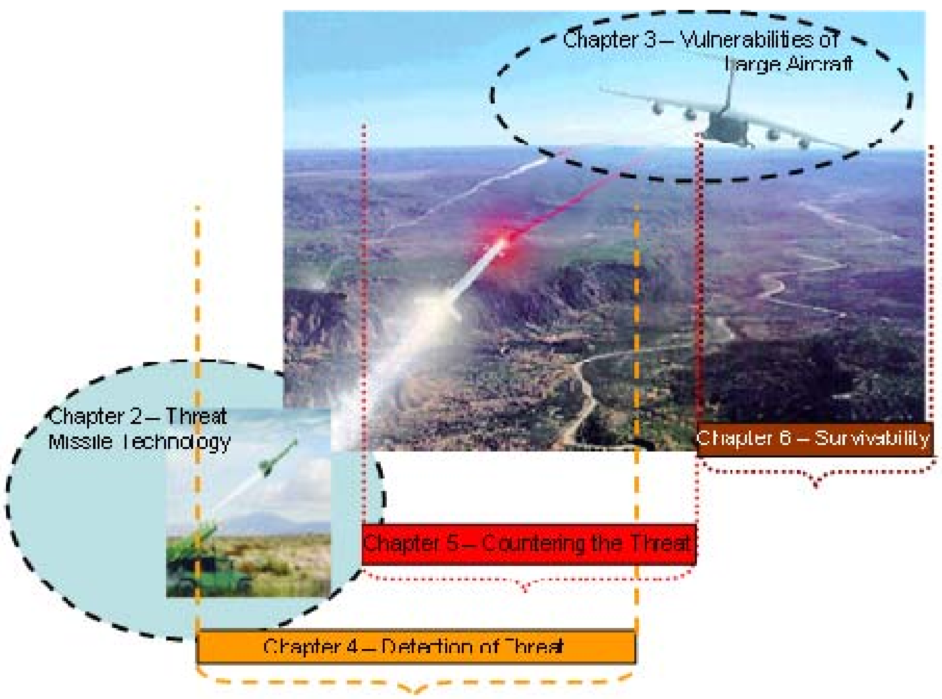


Figure 1. Organization of chapters.

Examples, but not necessarily all possible examples, of current systems are described, embedded in the pertinent sections, within the format shown in Table 1.

System Name	(Company Name)
Description:	Brief description of the system
Features:	Special features

Table 1. Example of a system application.

II. MISSILES AS A THREAT

A. MISSILES

Missiles are categorized according to their guidance features. SAMs are used for shooting down flying objects and, as a second objective, seeking virtual attrition, which means preventing the enemy from executing its mission. Aircraft fly high to avoid being shot down because the precision and accuracy of unguided missiles decrease with altitude. Guided missiles were developed against aircraft because artillery systems became insufficient to shoot down a high-flying target. Guided missiles opened a new era in air defense, in terms of accuracy, precision and shoot-down rates of potential attacks. A missile block diagram is in Figure 2.

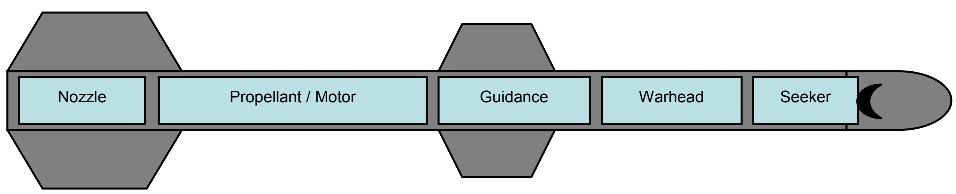


Figure 2. A typical guided missile.

The radome protects the antenna or sensor of the seeker and reduces drag. The seeker detects the target and generates signals for the guidance system. The warhead consists of explosives to destroy the target. The fuze assures the detonation of the warhead if it does not hit the target and explode directly. The guidance system commands the control fins. To hit an aircraft, a missile has to carry out some consecutive stages. The aircraft should be searched for, detected, and tracked. Then, the missile should be launched and flown out to the target. The most challenging electromagnetic aspects of these processes occur in the early warning, acquisition and flyout phase of missile because most electronic warfare happens in this region.

The effectiveness of the missile is directly related to its flight performance, guidance type, trajectory, fuze, warhead and sensor it uses.

B. PHASES OF MISSILE GUIDANCE

Almost all SAM systems have three phases during flyout: boost, mid-course, and terminal.

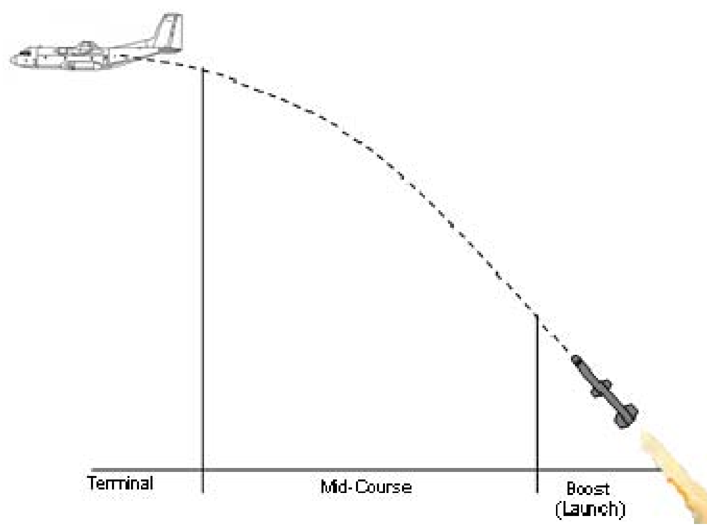


Figure 3. Phases of missile guidance.

1. Boost (Launch)

During the boost phase, the guidance systems are usually disabled to allow the missile to safely travel away from the launch platform.

Unless the missile employs a propulsion system that does not emit heat sources, it emits visible, infrared (IR) and ultraviolet (UV) signatures from the exhaust and the exhaust plume of the missile during the launch phase. Those signatures are the most important indicators for missile launch detection by the countermeasures systems.

2. Mid-Course

The missile spends most of its flight time in the mid-course phase. Using the guidance system, the missile makes slight adjustments to intercept its target.

3. Terminal

The missile maintains accurate tracking to intercept the target in the terminal phase.

The boost and mid-course (or sustain) phases provide the most characteristic emissions in the optical bands. During the terminal phase, the signature becomes less or burns out. "Discrete frequency emissions from rotational and vibrational transitions of water vapor and carbon dioxide molecules account for much of the exhaust emission."[2] Those observables are the most important detection and guidance information for missile warning receivers (MWRs.)

C. MISSILE GUIDANCE TYPES

Guidance is the vital issue in missiles since it steers the missile from the surface to the maneuvering aircraft.

Different types of missiles are classified according to their guidance types. Typically, different resources may slightly rearrange the classifications but, generally, the types of guidance are: active, semi-active, command, beam-riding, retransmission, passive, and imaging guidance. Some missiles employ more than one guidance method during the different flight stages.

[2] Accetta and Shumaker, 1993, 18.

1. Active Guidance

a. System Principle

In active guidance, the missile has its own small radar. Since the radar is built into the missile, there is no need for an external data or command to be followed. But in application, this function is not used during the whole flight. Once a missile is fired, it travels to the general area of the target by means of inertial or command guidance, then turns on its radar, acquires the target, and guides itself to impact with the target. Usually, missile radars are used in the last ten kilometers of the attack. i.e., in the terminal engagement.

b. Pros

The platform firing the missile can leave the area immediately after launch. Since they do not need any assistance after launch, they are also called “fire and forget” missiles. Guidance becomes more accurate as the range to the target diminishes.

c. Cons

These systems are heavier and more expensive. They can be used only once. They radiate radio frequency (RF) energy, which means they can be detected by a simple radar warning receiver (RWR).

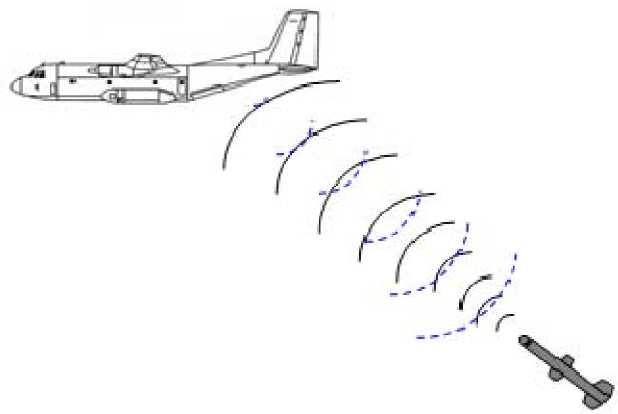


Figure 4. Active guidance.

d. Susceptibilities to Jamming

These modern systems are equipped with pulse Doppler radar and become very hard to jam at close range (because the radar power on the target is an inverse function of range).

$$P_{atJammer} = \frac{P_t \cdot G_t \cdot \lambda^2 \cdot G_j}{(4\pi R)^2 L_p}$$

In Table 2, some of the missiles, which use active guidance in their particular phase of flight and sensor type, are shown.

Missile Name	Phase of Flight	Sensor
SA-5	Terminal	RF
MBDA Aster	Terminal	RF
MEADS	Terminal	RF
Patriot(PAC3)	Terminal	RF
HQ7		RF+IR+TV
Roland		RF

Table 2. Some missiles that employ active guidance.

2. Semi-active Guidance

a. System Principle

In semi-active guidance, there is no transmitter aboard. Signals transmitted by a ground or air defense system radar are scattered from both the target and other objects. The receiver on the missile receives the scattered signals. Only reflected aircraft signals can pass through the Doppler filter. Radar illuminates the target by a continuous wave (CW), interrupted continuous wave (ICW), or high pulse repetition frequency (PRF) pulses. ICW permits control of more than one missile. Semi-active guidance operates similar to bistatic radar or a laser-guided weapon.

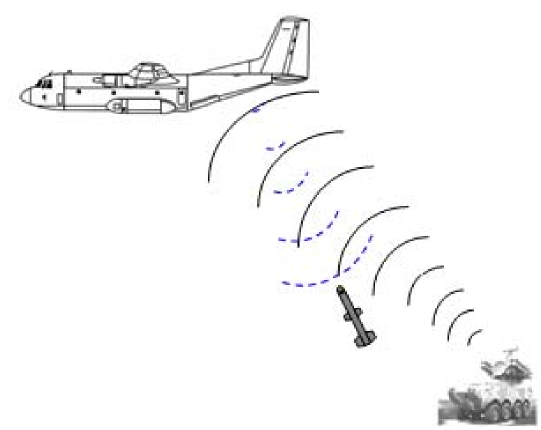


Figure 5. Semi-active guidance.

b. Pros

Since the missile follows the reflected signals, the illuminating source should not stop transmitting. The seeker and the maneuverability of the missile have greater roles in hitting the target precisely.

c. *Susceptibilities to Jamming*

A CW system may calculate the angle data in a narrow band. The extremely narrow processing band (1 kilohertz on a carrier of many gigahertz) prevents the system from being jammed easily. When the missile fire control turns on its illuminator, this usually means that a missile launch is near. While the missile is in flight, either the tracking radar must be forced to break lock, or the missile must be jammed. A conical scan missile seeker is more susceptible to jamming than a monopulse one.[3]

Obscuration of the illumination terminates the lock. For example, a low-flying aircraft can maneuver behind a terrain feature to obscure itself from the radar.

In Table 3, some of the missiles, which use semi-active guidance in their particular phase of flight and sensor type, are shown.

Missile Name	Phase of Flight	Sensor
SA-4	Terminal	RF
SA-6	Terminal	RF
SA-11		RF
SA-N-6		RF+IR
SA-12		RF
SA-17		RF
Aspide (multirole)	similar to AIM-7	RF
Bristol Bloodhound		RF
HQ-9		RF
HAWK		RF
RIM-7		
RIM-66M	Terminal with passive, (Midcourse Inertial)	RF+IR
RIM-156	Terminal	RF
RIM-161	Terminal with passive	RF+IR
RIM-162	Terminal	RF
Sea Dart		RF

Table 3. Some missiles that employ semi-active guidance.

[3] Filippo Neri, *Introduction to Electronic Defense Systems*, 2nd ed. (Boston, MA: Artech House, 2001), 239.

3. Command Guidance

a. System Principle

A missile seeker is not required. The missile depends on another platform to receive commands regarding where to go. There are two radars: one for tracking the target and one for missile guidance. If a single radar is employed for both duties, then the missile is commanded to stay within the radar beam, which is called command-to-line-of-sight (CLOS). The computer calculates received positions of the missile and the target to generate the missile's trajectory for the impact point. A missile sensor, which is mounted on the platform, tracks the target and calculates its path of flight. Then the missile explodes at the aircraft's predicted position.

The further away from the energy source, the greater the degradation of accuracy and guidance. The target must be illuminated often enough to assure guidance effectiveness, but this inhibits the ability to engage more targets. Some missiles use more than one guidance method. For example, command guidance may be used for mid-course and active guidance for the terminal phase.

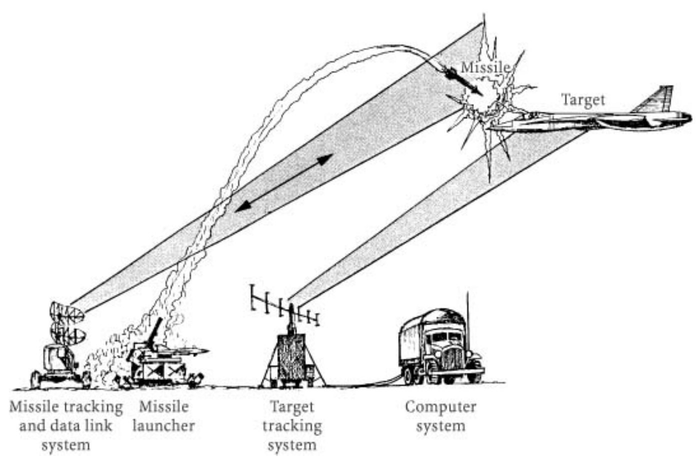


Figure 6. Command guidance.[4]

[4] Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, 388.

b. Pros

This system is simple and the missile is relatively cheaper since it does not have a seeker.

c. Cons

The power and accuracy of the missile-tracking radar is essential to guide the missile precisely. As the radar-to-target range increases, the effectiveness of the system decreases due to angular accuracy between the two radars. Therefore, they are mostly used in short-range missiles.

d. Susceptibilities to Jamming

The data link can be jammed.

In Table 4, some of the missiles, which use command guidance in their particular phase of flight and sensor type, are shown.

Missile Name	**Phase of Flight**	**Sensor**
Nike Hercules		RF
Patriot	Mid-course(TVM)	RF
SA-1		RF
SA-2		RF
SA-3		RF
SA-4	Mid-course is command	RF
SA-5	Mid-course (Terminal active)	RF
SA-6	Mid-course	RF
SA-8		RF
SA-15		RF
Akash		RF
Barak		RF
KS-1		RF
Rapier	+passive	RF+IR
Sea Cat	CLOS via a radio link	
Sea Wolf		RF
Crotale	+TVguidance (regular+IR)	RF+IR
Trishul		RF
Starstreak	SACLOS	

Table 4. Some missiles that employ command guidance.

4. Beam-riding Guidance

a. System Principle

There is one radar for tracking the target and the missile has only an onboard receiver. The missile always centers within the radar beam; therefore, as the radar track's boresight moves, the missile continuously aligns itself. Since the missile is faster than the target, eventually, the intercept occurs. This often requires very large missile maneuvers, so it is not commonly used in airborne missile guidance. Integrated closed-circuit TV may improve system performance. Laser usage is becoming more common since its dispersion by range is less and it is more difficult to detect laser illumination than it is to detect RF. Laser beam-riding missiles follow a laser beam and they cannot be jammed easily.

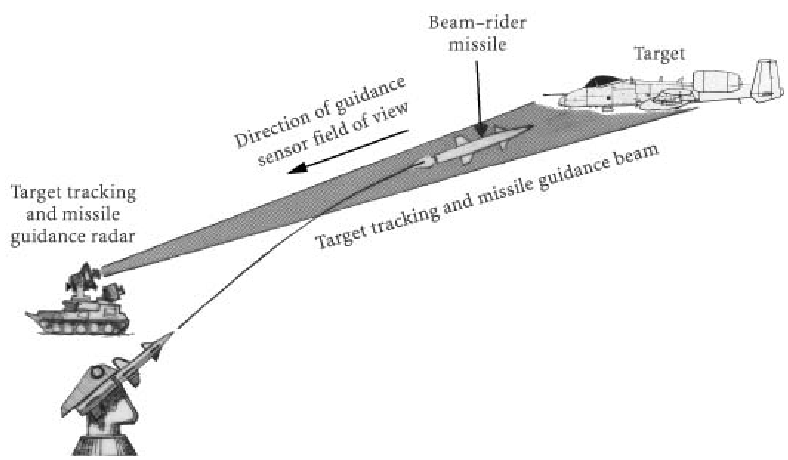


Figure 7. Beam-riding guidance.[5]

[5] Ball, 389.

b. Pros

It is a simple system. There is no need to command-link. Many missiles can follow one beam.

c. Cons

Since it follows the radar beams, even if the target flies a straight path, the missile makes many maneuvers, which causes speed loss and long flight time. The beam must be very narrow; otherwise, it will not be precise. This dictates a short-range system.

In Table 5, some of the missiles, which use beam-riding guidance in their particular phase of flight and sensor type, are shown.

Missile Name	Phase of Flight	Sensor
Terrier(RIM2-C)		
ADATS	Digitally coded laser beam	Laser
Sea Slug		RF
RBS70	Laser beam	Laser
Starstreak	Laser beam	Laser

Table 5. Some missiles that employ beam-riding guidance.

5. Inertial Navigation Guidance

This type of guidance navigates with onboard gyros and accelerometers. Mostly, it is used for the launch and mid-course phases of a missile’s flight. Then, beginning from the late period of mid-course to the terminal phase, more precise guidance methods are used.

In Table 6, some of the missiles, which use inertial navigation guidance in their particular phase of flight and sensor type, are shown.

Missile Name	Phase of Flight
CLAWS	(HUMRAAM) mid course (terminal active RF)
MEADS	Mid-course
Nike Hercules	Mid-course

Table 6. Some missiles that employ inertial navigation guidance.

6. Retransmission Guidance

a. System Principle

The radar system illuminates the target and both the ground radar system and the missile's receiver receive reflected signals from target. The target information is also relayed from the missile to the ground system via downlink. Therefore, this system is also called, "track via missile" (TVM). The principle of retransmission guidance is similar to semi-active or command guidance.

b. Pros

A two-way link between the missile and the ground station enables precise and flexible tracking.

c. Cons

Complexity. Some TVM systems have problems tracking targets at very low altitudes due to line-of-sight problems between missile and ground station.

d. Susceptibilities to Jamming

Two-way links can be jammed.

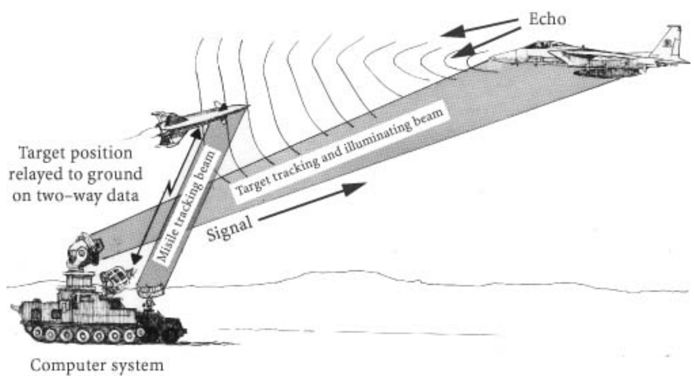


Figure 8. Retransmission guidance.[6]

In Table 7, some of the missiles, which use retransmission guidance in their particular phase of flight and sensor type, are shown.

Missile Name	Phase of Flight	Sensor
Patriot(PAC-2)	Terminal	RF
SA-10		RF
MBDA Aster	Mid-course	RF
RIM-162	Mid-course	RF
SA-20		RF

Table 7. Some missiles that employ inertial navigation guidance.

7. Passive Guidance

a. System Principle

In passive guidance, the missile homes in on some emission from the target. Infrared missiles, anti-radiation, and home-on-jam missiles are good examples. Once the track is established and the missile fired, then, as in active guidance, the launching platform can leave the area.

[6] Ball, 391.

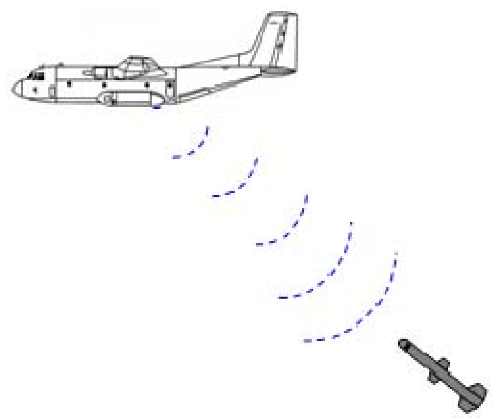


Figure 9. Passive guidance.

b. Pros

They are relatively simple and cheaper systems. Once they are fired, there is no more ground guidance.

c. Cons

They have shorter ranges.

d. Susceptibilities to Jamming

They are very susceptible to jamming because the radiation can be imitated easily.

In Table 8, some of the missiles, which use passive guidance in their particular phase of flight and sensor type, are shown.

Missile Name	**Phase of Flight**	**Sensor**
Stinger		IR/UV
RAM	Terminal: Passive IR	RF/IR
SA-7		IR
SA-9	Passive IR	IR
SA-13		IR
SA-14		IR
SA-16		IR

Missile Name	Phase of Flight	Sensor
SA-18		IR
Redeye	Tail chase only	IR
Chaparral	Aim-9 based Passive	IR
Anza		
Mistral		IR
Umkhonto	All-aspect IR	IR
RIM-116	Passive RF/ Passive IR	IR+RF

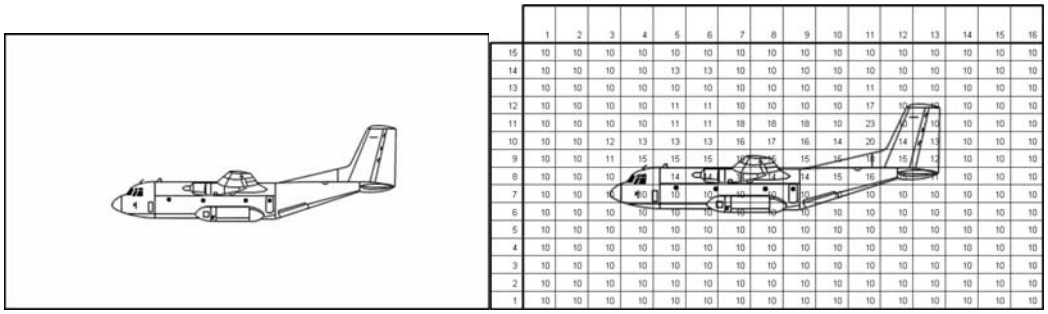
Table 8. Some missiles that employ passive guidance.

8. Imaging Guidance

In guidance methods, the trend is towards using imaging guidance for relatively short distances. Therefore, this topic is emphasized more than others.

An imaging-guided missile captures the image of a target and centers that image in its field of view. Imaging guidance can come in different types, such as television (TV), scanning IR, staring IR imager, and correlation trackers. SAMs may use correlation trackers and typically use a 3–5 μm range.

An automatic video tracking system maintains a stable line of sight. The target is recognized by either a manual or an automatic target recognition system. In Figure 10, there is an aircraft in the missile's field of view. The values in each pixel come from the signals generated by the detectors.



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4	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
3	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
2	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
1	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

Figure 10. Image tracking.

The centroid of the target can be defined as the binary or intensity centroid.

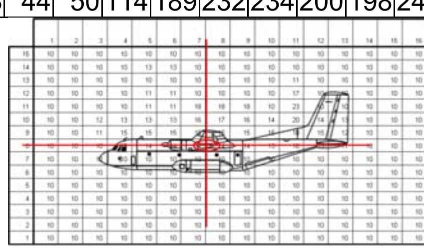
In Figure 11, the background, which has the value of 10, is eliminated by binary thresholding. After thresholding, the binary values are multiplied by the related row or column numbers. Then the values are added. The formula is as follows.

$$x\_centroid = \frac{\sum_{i=0}^{m} xposition_i}{\sum_{j=0}^{n} N_j}$$

$$y\_centroid = \frac{\sum_{i=0}^{m} yposition_i}{\sum_{j=0}^{n} N_j}$$

The intensity or weighted centroid is calculated by first removing background, then following the same procedure as in binary centroid. This gives a more consistent track point for the missile to guide by always centering the target in the center of the image. Imaging seekers provide resolution that is required to separate the target from expendable countermeasures.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		Intensity Centroid	
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
12	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0		6	72
11	0	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0		5	55
10	0	0	0	0	0	0	0	0	0	0	0	4	3	0	0	0		7	70
9	0	0	0	1	1	3	4	5	3	3	4	5	2	0	0	0		31	279
8	0	0	1	5	4	10	13	13	12	8	8	6	4	1	0	0		85	680
7	0	0	5	4	4	5	6	7	9	8	6	0	0	0	0	0		54	378
6	0	0	0	1	1	1	4	4	2	1	0	0	0	0	0	0		14	84
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
																		202	1618
	0	0	6	11	10	19	27	29	26	20	18	20	15	1	0	0	202		
	0	0	18	44	50	114	189	232	234	200	198	240	195	14	0	0	1728		



The area balance track point

xbar= 8.554455

ybar= 8.009901

Figure 11. Centroid Image.

Missile Name	Phase of Flight	Sensor
Crotale	TV(Regular+IR)+Command	RF+IR

Table 9. A missile that employs imaging guidance.

D. MISSILE TRAJECTORIES

1. Pursuit

The missile follows the target as long as the line of sight between missile and target is established. It ends up in a tail-chase situation. Therefore, the speed of the missile must be greater than that of the target. In the terminal phase, before ending up in a chase situation, the missile must be agile. There are two main reasons for this. First, due to the arrival angle of the missile, it must make a sharp turn to intercept. Second, the target will likely attempt to terminate the lock-on by maneuvering. These reasons make pursuit trajectory useful against slow-moving aircraft. Also, it is effective for tactical aircraft if the missile is launched from a point directly to the rear of the target or head-on toward an incoming target. Because, in this case, the approaching angle between the missile and target is 0 degrees, it enables the missile to go straight.

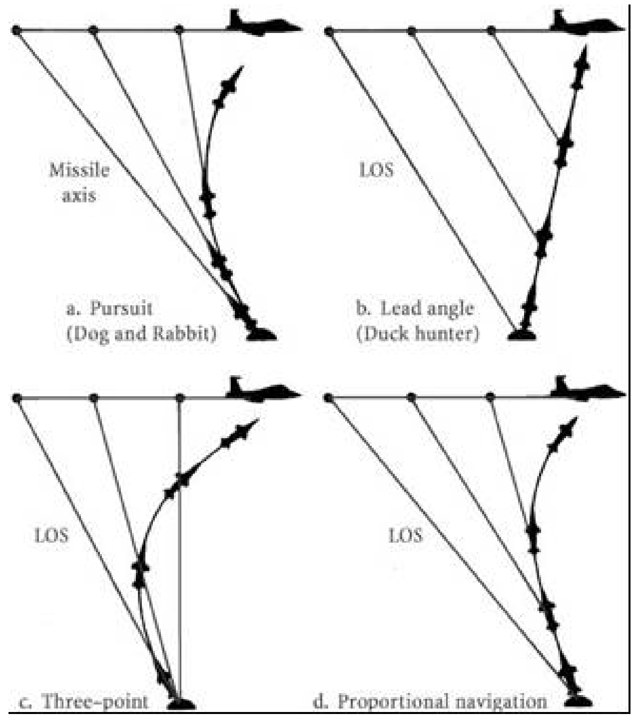


Figure 12. Types of trajectories.[7]

2. Lead Angle

A lead trajectory is calculated based on the target's flight path. If there is no bearing change in the flight path of the target, the trajectory of the missile will be a straight line. On the other hand, if the target's path changes, then the missile recalculates the new bearing to fly toward.

3. Three-Point

Three-point trajectory is used only for short-range missiles using CLOS or beam-riding guidance. When the missile, tracking platform and target are thought of as points, they are always aligned to form a straight line.

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7 Ball, 394.

4. Proportional Navigation

Sharp turns and continuous maneuvers cause the missile to lose speed and energy. Proportional navigation enables the missile to make small maneuvers at the beginning of the trajectory. Then, as the missile approaches the target, the proportional constant and the intercept angle increase, therefore minimizing the energy loss in the early stage of flight. The missile is always seen at a constant look angle from the target.[8]

For the detection of a missile, the approach angle and the instantaneous image of the missile become more important. In electro-optics, the intensity of plume emissions varies with many factors, such as the angle of the missile relative to the receiver as well as the altitude and velocity of the missile.

Pursuit guidance is not as effective as proportional navigation but it is simpler in mechanization developments. The missile velocity is important in pursuit guidance since the engagement always ends up in a tail-chase and the missile travels the longer distance. In the example shown in Figure 13, a non-maneuvering target is hit by two missiles, one of which employs proportional navigation while other uses pursuit navigation. Pursuit navigation has a tremendous curvature. Therefore, it needs large acceleration and maneuvering, which reduces its kinetic energy and its range.

[8] Ball, 395.

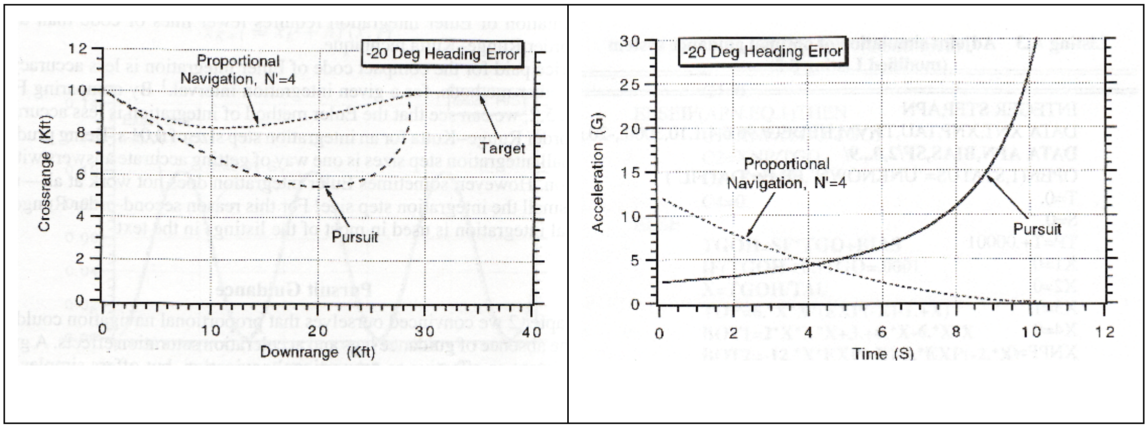

Figure 13. Pursuit vs. proportional navigation.[9]

E. MISSILE FUZING

A fuze detonates a high-explosive (HE) warhead when the missile is in the vicinity of the target or at the impact moment. The HE creates a blast wave and high-velocity metal fragments

1. Time Fuzing

This method initiates detonation after a preset elapsed time, which begins with the launch time. Missiles have limited fuel, which is one of the factors that defines their range. After burnout and losing its energy, it begins free-falling. Therefore, time fusing also enables the self-destruction of a missile when it misses the target, preventing possible collateral damage.

2. Contact Fuzing (Hit-to-Kill)

In contact fuzing, detonation occurs at the impact moment. For a more effective explosion, a short delay can be applied, which detonates the HE warhead after it is actually inside the aircraft.

[9] Paul Zarchan, *Tactical and Strategic Missile Guidance*, 5th ed. (Reston, VA: American Institute of Aeronautics and Astronautics, 2007), 772.

3. Proximity Fuzing

With proximity fuzing, the HE warhead is detonated by a target detection device (TDD) when it is in the vicinity of the aircraft. The TDD can detect the proximity with either the missile's system or its own.

Warhead diameter and weights are important criteria for assessing the vulnerability of aircraft and its lethal range. Some SAM warhead's capabilities are shown.

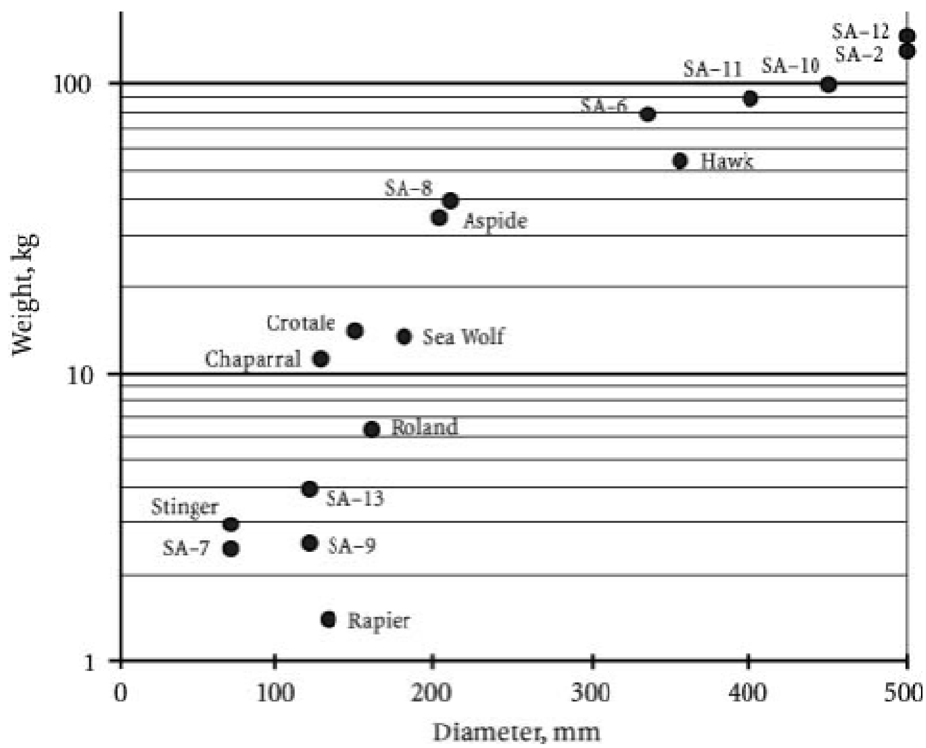

Figure 14. SAM warheads and their diameters.[10]

F. ELECTROMAGNETIC SPECTRUM AND SENSOR TYPES (DETECTORS)

Sensors are the most important part of a missile. It is just like a sensation system in humans. If the sensor can be deceived, then the missile cannot reach

10 Ball, 316.

its target. Different types of missiles use different sensor technologies but, for the time being, they all use the RF and/or electro-optical regions of the electromagnetic spectrum. Therefore, the technology behind the sensors is important since the counter missile actions must also take place in the electromagnetic spectrum. Figure 15 shows the wide range of the EM spectrum, from radio waves to gamma rays. Although there are no exact boundaries between the regions, commonly accepted regions are:

Ultraviolet: 10 nanometers–0.4 micrometers

Visible: 0.4–0.7 micrometers

Infrared: 0.7–14 micrometers

Frequency is used in the RF portion and wavelength is used in the optical portion of the spectrum. However, the speed of the light is a common formula in which they are related.

$$c = \lambda \cdot f$$

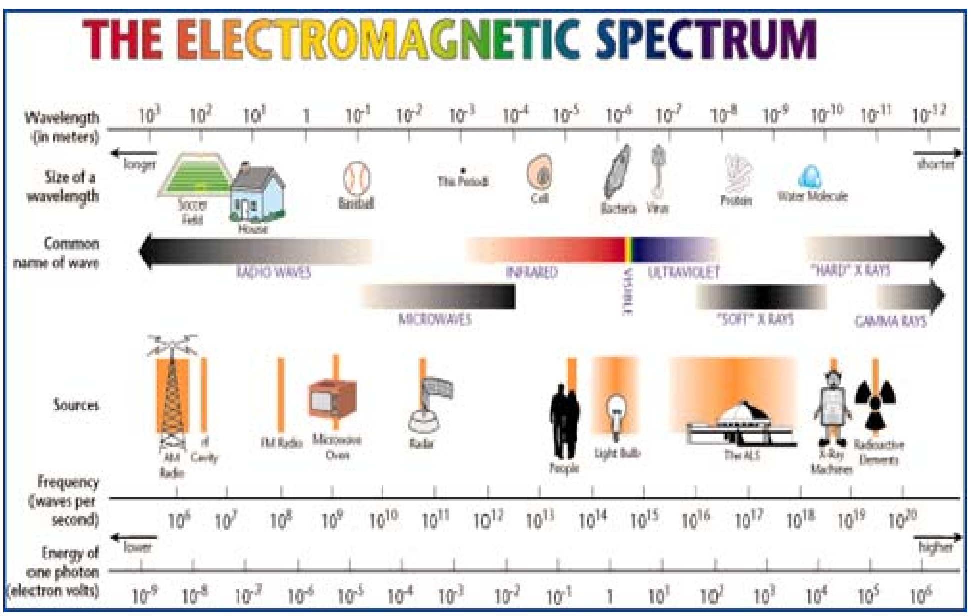

Figure 15. Electromagnetic spectrum.[11]

[11] Electro Optical Industries Inc., "EM spectrum," http://www.electro-optical.com/html/bb_rad/emspect.asp (accessed 15 November 2007).

The electronic receivers of a guided missile can be deceived in three different ways: annihilating the target signature, obscuration and attenuation in the medium, and deceiving or destroying the sensor. As is illustrated in Figure 16, a target produces or reflects signatures; the atmosphere enables those signals to be propagated and the seeker tracks those signals. The missile and the aircraft compete to prevail in this rivalry on the basis of three subjects in the EW spectrum and propagation techniques.

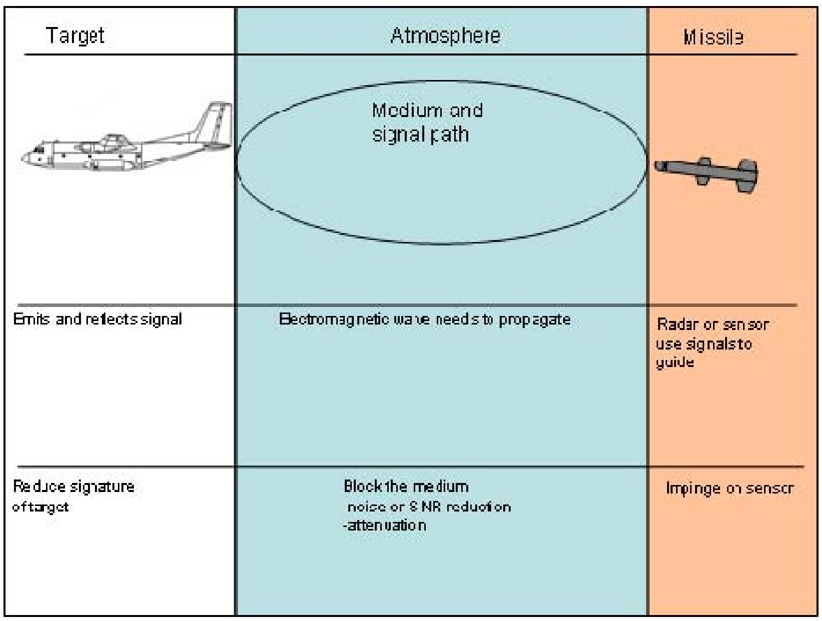

Figure 16. Missile-target engagement in the EM spectrum.

1. Radar

There are many effects that change the performance of radar, such as signal reception, receiver bandwidth, pulse shape, signal-to-noise ratio, receiver sensitivity, beamwidth, pulse repetition frequency, radar cross-section (RCS) of target, pulse compression, scan rate, antenna gain, carrier frequency, and antenna aperture.

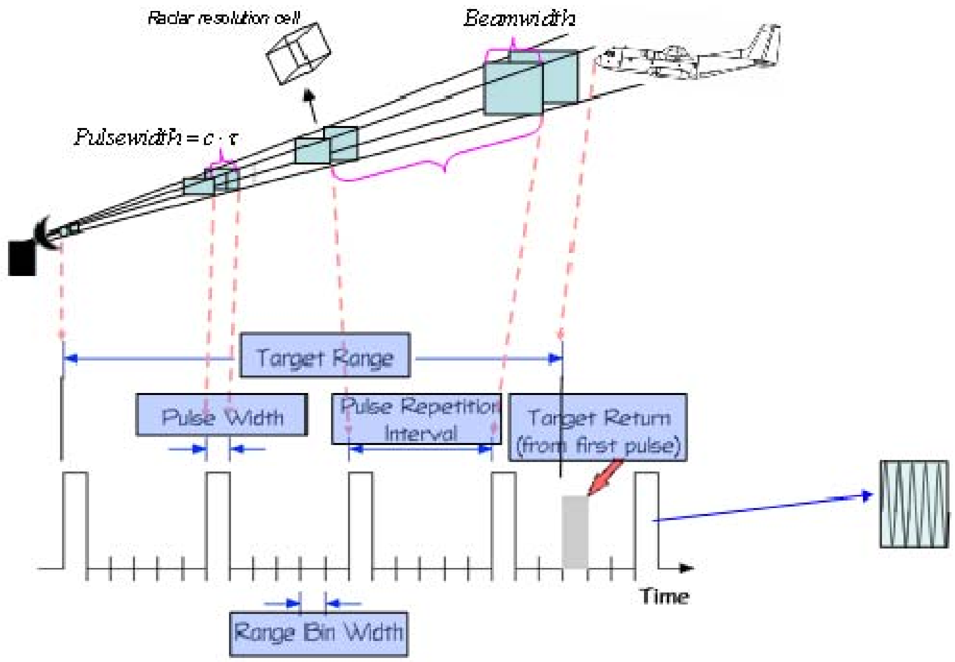

Figure 17. Radar principle.

The radar resolution cell is an important factor in break-lock calculations and in determining the resolution range when multiple aircraft are approaching.

2. Electro-optics

Electro-optics is a term that is used for a portion of the electromagnetic spectrum, namely wavelengths between 1 millimeter and 1 nanometer. This includes infrared, ultraviolet and the visible region. However, in the EW world, electro-optics is a term used for UV.

a. Infrared

All substances absorb and radiate IR energy, provided they are not at a temperature of absolute zero (0° K). The hot objects emit more energy and the peak wavelength of emission decreases as T^{-1}. IR energy has the same features as visible light in terms of traveling in a straight line at $3x10^8$ m/s and

being reflected or absorbed when hitting the surface of an object. Polished surfaces reflect more IR energy. The principles of infrared are shown in Figure 18.

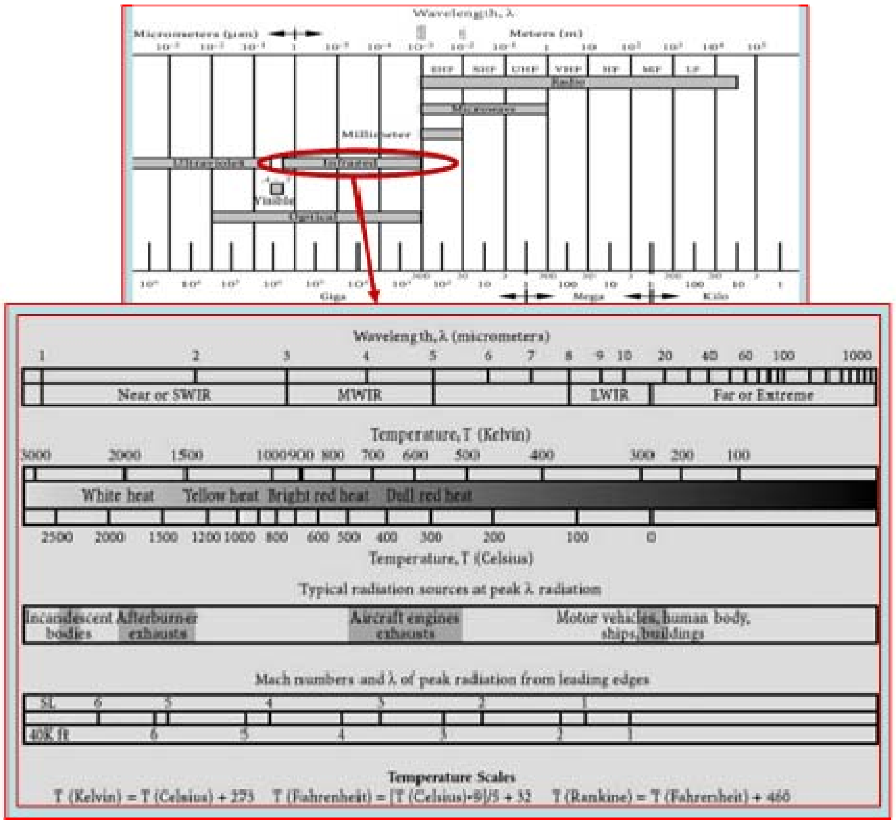

Figure 18. Infrared principle changed from the original.[12]

Just as in transparent materials, in which the visible light passes through, part of the IR energy striking a solid opaque material are absorbed, and some of them are reflected. Some of the energy absorbed by the material is converted to heat while some of them are reflected internally, as shown in Figure 19.

12 Ball, 359.

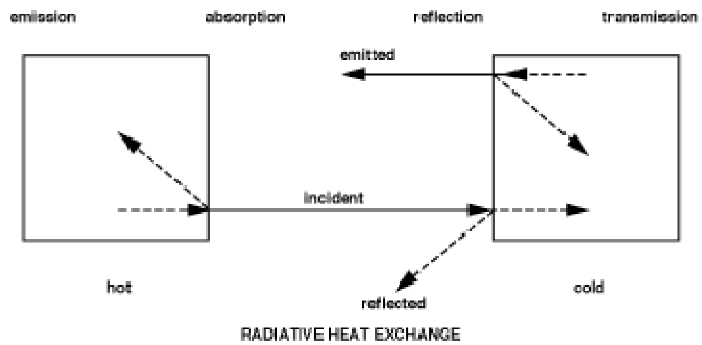

Figure 19. Radiative heat exchange.[13]

An ideal blackbody is a material that does not reflect or transmit any IR energy. It is an IR opaque and absorbs all radiant energy.

Emissivity (ε) is related to a material or gas' function of its molecular structure and surface and defined as the ratio of energy emitted by the material to energy emitted by a blackbody at the same temperature and shows the material's ability to absorb and radiate energy. The factors that affect emissivity of a material or gas are molecular structure, surface condition, and wavelength sensitivity of the sensor (sensor's spectral response).[14]

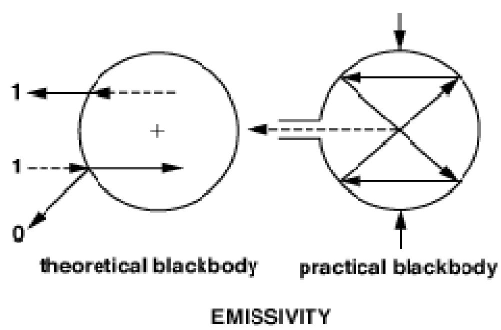

Figure 20. Emissivity.[15]

[13] Omega Engineering, "Infrared temperature measurement," http://www.omega.com/techref/iredtempmeasur.html (accessed 20 March 2008).

[14] Ibid.

[15] Ibid.

Highly polished surfaces reflect more IR energy but have much lower emissivity.

Transmissivity is the ratio of incident light coming from a source to intensity (time averaged energy flux) or wavelength. It is the ratio of transmitted radiant power to the incident radiant power. Absorptivity is the ratio of absorbed radiant power to incident radiant power. Reflectivity is the ratio of reflected radiant power to the incident radiant power.[16]

As we think about the concept of conservation of energy, the sum of the absorptivity, reflectivity and tranmissivity of a radiant power is equal to one.

Thermal detectors can measure the differences in the physical features of the detector, which is caused by the heating effect of the incident radiation. They are slower to respond in that they do not have high data rates where it is needed, in searching and tracking. They are not extremely sensitive but they do not need cooling.

Photon detectors have higher detectivity but they need cooling for optimum sensitivity. The optimum cooling is found for optimum wavelength coverage. The detectivity response of photon detectors changes with wavelength, which is shown in Figure 21. Photoconductors, photovoltaic detectors, charged coupled devices, and charge injection devices are types of photon detectors.

[16] Alfred Cooper, “EO-IR Countermeasure Systems Class Notes PH4209,” 2007.

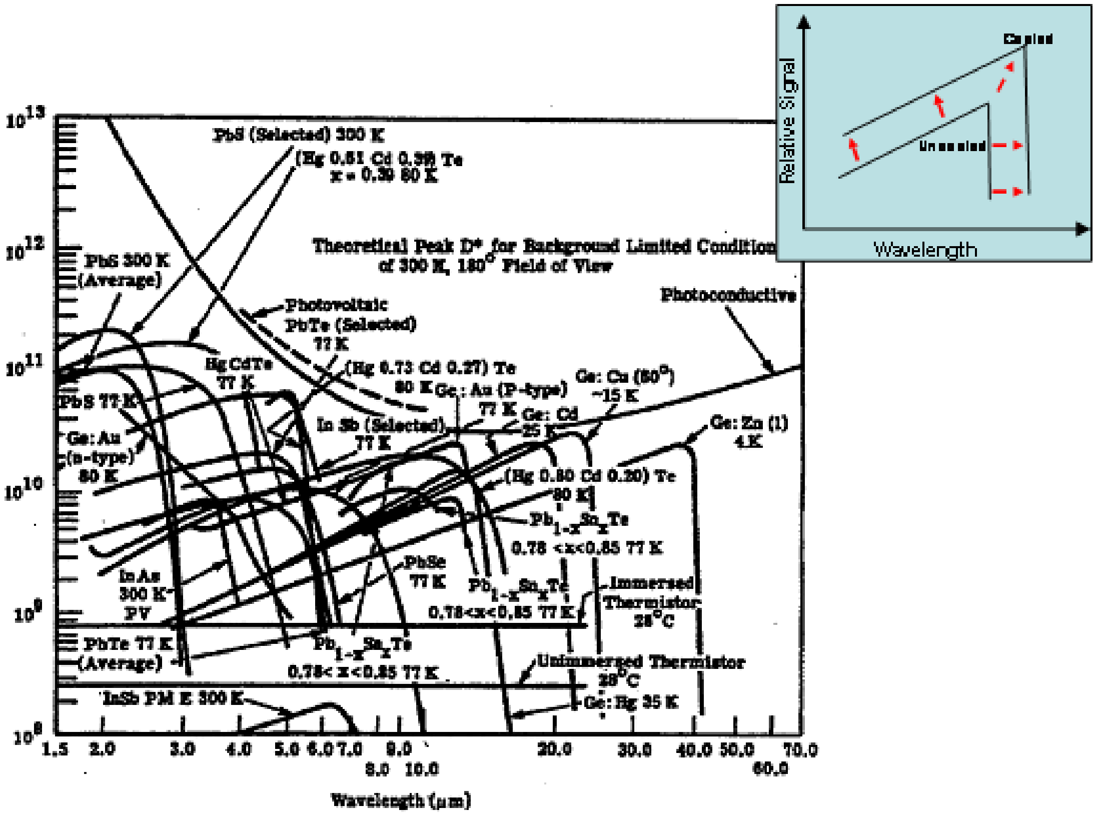

Figure 21. Detectivity plot of photon detectors.[17]

The important formulas related to infrared are as follows:[18]

1. Kirchoff's Law. When an object is at thermal equilibrium, the amount of absorption will equal the amount of emission.

2. Stephan Boltzmann Law. The hotter an object becomes the more infrared energy it emits.

$$P_{total} = \sigma \cdot \varepsilon \cdot A \cdot T^4$$

3. Wien's Displacement Law. The wavelength at which the maximum amount of energy is emitted becomes shorter as the temperature increases.

$$\lambda_{\max} = \frac{2898}{T(K)} \mu m$$

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[17] Cooper.

[18] Omega Engineering.

Figure 22 shows propagation of electromagnetic radiation in the atmosphere. As you can see, while visible light can penetrate Earth's atmosphere and reach sea level, UV is the most absorbed. Therefore, it is very effective to detect a missile plume where this phenomenon eliminates most of the background.

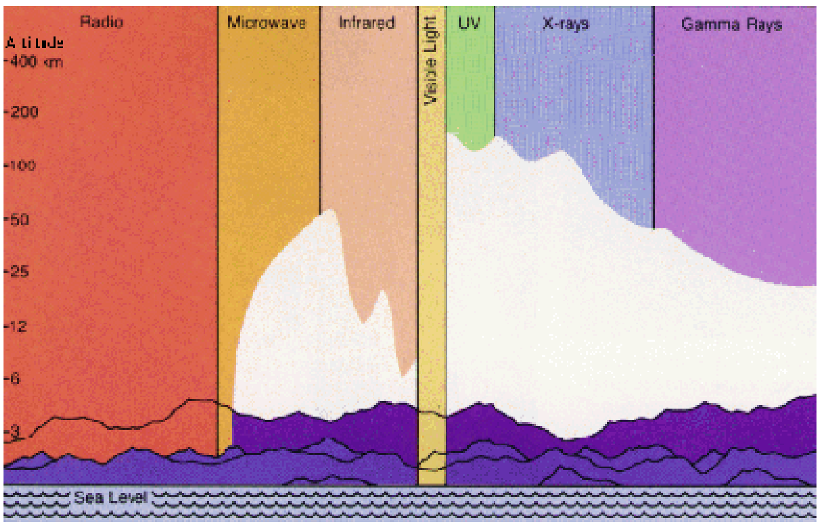

Figure 22. Propagation of EM.[19].

b. Ultraviolet

The UV region starts from 10 nanometers to 0.4 micrometers. UV technology is used usually in warning systems to detect the missile plume. Because as it can be seen in Figure 22, background coming from the sun is blocked by the atmosphere. Reducing the signal processing provides a big advantage.

[19] Electro Optical Industries, Inc.

c. Laser

Laser (light amplification by the stimulated emission of radiation) can be used in different applications. An aircraft can be illuminated by a laser, which is used for range finding, target designation, target illumination, or beam-riding. Different types of laser applications, pertinent laser types, and wavelengths are shown in Figure 23.

Range measurement: The principle is the same as in radar. The time elapsed between the transmitting of a laser pulse and the return of the reflected echo is used for range calculation.

Target illumination: A missile with a laser receiver can home onto a target illuminated by the laser.

Guiding illumination: The missile follows the route as in the beam-riding type. The receiver onboard the missile guides it and guarantees that it is on the laser beam at all times.

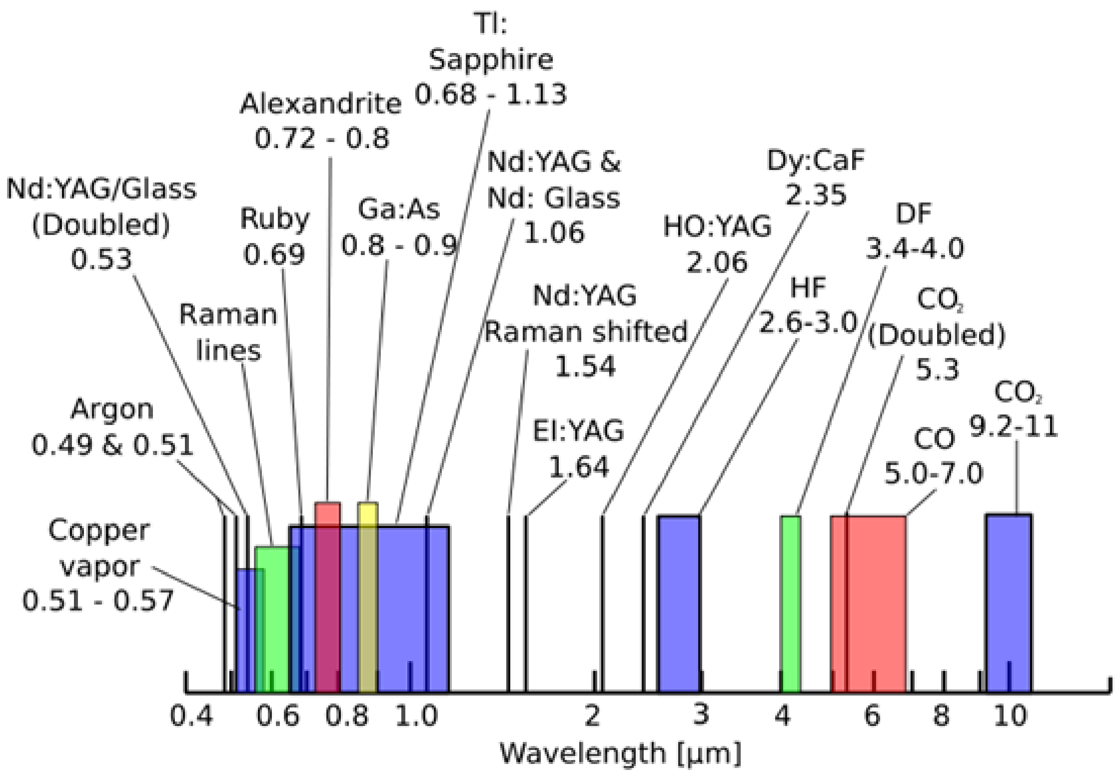

Figure 23. Laser spectral range.[20]

Restrictions are atmospheric attenuation and low efficiency due to the characteristics of the laser. These restrictions mean that lasers are mostly used in short-range missiles (3–10 km).[21]

3. Aural Detection

In Figure 24, World War II air defense operators try to detect the target and its arrival direction. Sound has different properties than light. Since it has a very low propagation speed, it cannot meet today's demand. But since large aircraft and helicopters travels at slower speeds, it can still be an effective method if acoustic sensors are placed on possible flight routes. Moreover, most

[20] Wikipedia contributors, "Laser spectral lines," http://en.wikipedia.org/wiki/image:laser_spectral_lines.svg (accessed 20 March 2008).

[21] Neri, 2001, 257.

of the time, it cannot be suppressed; from the missile perspective, it gives a good tracking signature if the delay problem due to propagation can be solved.

Figure 24. Acoustic tracking antenna.[22]

4. Visual Detection

The human eye is reliable for detection of threats. The contrast between the aircraft and the sky, or from smoke emissions and contrails, easily reveals an aircraft’s position. Contrails have different sources, such as aerodynamic, convection, and engine exhaust, which occurs at approximately 30,000 feet.

G. EMERGING THREAT: MAN-PORTABLE AIR DEFENSE SYSTEMS (MANPADS)

IR seeker technology enabled the missile-independent, point-defense system. Their small size makes it cheaper as well as possible to rapidly change locations and create a threat anywhere. Therefore, they do not require anywhere near as complicated a system to use as in RF technology. For these reasons,

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22 Time-Life Video. *Stealth, Great Fighting Jets*, V648-01.

MANPADs have proliferated widely. While a missile costs around $30 thousand, it can shoot down a $30 million aircraft. Threat size, location, cost and effects combine to create an asymmetry between MANPADs and aircraft. MANPADs are threatening not only to military aircraft but also to civilian airliners. They are cheaper to buy and are easy to carry and operate. They employ the passive guidance method, using IR detectors. IR is effective over a short distance.

An operator visually acquires the target and tracks it to enable the missile to lock-on using IR. The IR acquisition signal is electronically processed and is presented to the operator as either an audible or visible signal when the seeker acquires enough IR energy of the target.

First-generation missiles have a peak detection sensitivity of 2 μm, which can detect a hot turbine from the rear aspect, in other words, an engine's tail pipe. As the detector technology developed, the missiles gained more capabilities. The 1.9–2.9 μm band was used in first-generation missiles with limited capabilities, such as only tail-aspect target engagement. At that time, cooling was the problem. After the cooling problems were solved, operating bands shifted through the mid-IR region of 3.0–5.0 μm, which enabled attacking from all aspects.

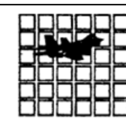
	Generation	Detectors	Peak Sensitivity	Examples	Signature Source and Engagement Aspect	Notes	
1960 1970	**1st Generation** Reticle chopping seekers (Gyro and reticle spins) Redeye, SA-7, HN-5	Uncooled lead-sulfide	2-2.7 μm IR	SA-7	Hot Turbine Tail	Sun	
1980	**2nd Generation** Reticle chopping seekers (gyro and mirror spins) Stinger, SA-14, SA-16, FN-6	Indium antimonide	3-5 μm IR-UV	SA-13	Any quarter	Effective against flare	
1990 2000	**3rd Generation** Pseudo-imagers and multi-color Quasi image Matra, SA-18, Anza MKII, Stinger B	Mercury cadmium telluride	8-10 μm IR-UV	SA-18		Flare immune	
2010	**4th Generation** Full imagers and multi-mode FPA, quadrant Stinger Block II		IR-UV	Keiko SAM		Area balance weight control rejects flare decoy	 KEIKO SAM

Table 10. Generations of IR missiles.

Different types of missile seekers are spin scan, conical scan (conscan), rosette, focal plane array, and quadrant detector seekers.

Spin scan: a reticle spins on the telescope of a spinning gyro and the blur image of the target produces signals as it goes through slots of the reticle. The disadvantage is that when the image is on boresight, the signal becomes insufficient and when the image is in center, there can be more noise.

Conscan: a target image reflected by a mirror, which spins with a gyro, passes through a stationary circularly symmetrical reticle and produces modulated signals. It has zero tracking error compared to a spin-scan seeker.

Rosette Scan Seeker: a detector scans a small instantaneous field of view (IFOV) at a time, in a pattern that makes many loops to cover the whole field of view (FOV). It has the advantage of resolving multiple sources in the field of view.

Focal Plane Array Seeker: multiple-element detectors make a scan of the target. Image tracking is possible by centroid or intensity weight of the FOV. Just as in television, a target has an area shown by pixels. When the pixels' positions are calculated with the intensity information, the target can be easily tracked. It has a better resolution than the reticle-type seekers and it may reject flares or IR decoys.

Quadrant detector seeker: a target image is detected by four detectors. The signal is proportional to the area of the target that is detected by one of the detectors. The missile makes maneuvers to balance the signals coming from the four detectors.

Name and Origin	**ID**	**Sensor**	**Range: H / V (km)**	**Speed (m/s)**	**Guidance & Warhead**
Stinger USA	FIM-92 A/B/C/D	2 Mid-IR & UV cooled InSb	8.0 / 3.8	729	Passive Homing & 450 g HE
GIMLET Russia	SA-16	2 Mid-IR & UV cooled InSb	5.0 / 3.5	662	Passive Homing & 390 g TNT
GRAIL Russia	SA-7A	Mid-IR Uncooled PbS	5.5 / 4.5	580	Passive Homing & 370 g HE
GROUSE Russia	SA-18	Mid-IR - cooled InSb & uncooled PbS	6.0 / 3.5	662	Passive Homing & 390 g TNT
GREMLINRussia	SA-14	Mid-IR Cooled PbS	4.1/--	470	Passive Homing & 390 g TNT

Table 11. Leading MANPADs.[23]

Figure 25 shows some of the arguments that the missile must discriminate in real life.

[23] James G. Sliney, "Ground-based Laser/Optical Countermeasures-MANPADs," http://ieeexplore.ieee.org/iel5/10454/33180/01563487.pdf, International Institute of Electrical Engineering (IIIE), 2005, (accessed 12 December 2007).

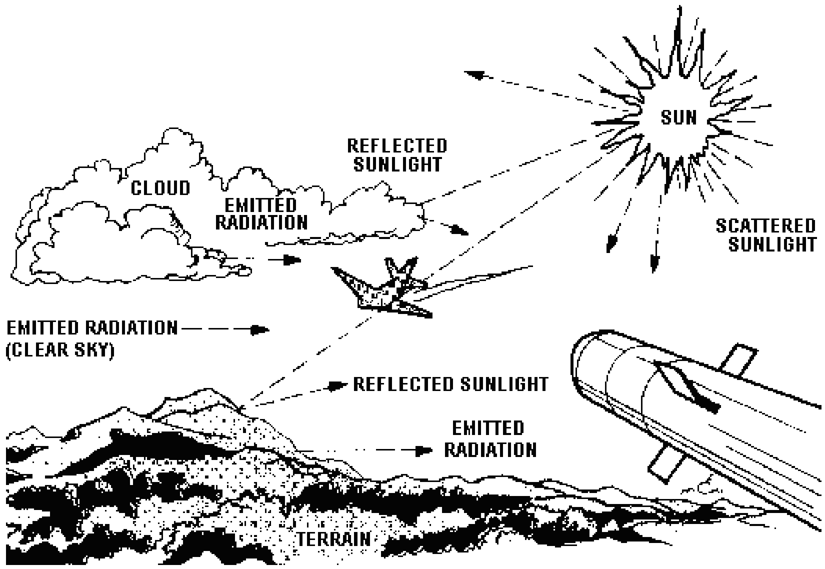


Figure 25. Stinger and environment.[24]

24 Global Security, "Firing the Stinger," www.globalsecurity.org/military/library/policy/army/fm/44-18-1/Ch3.htm (accessed 20 March 2008).

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III. SUSCEPTIBILITIES OF LARGE AIRCRAFT

Important attributes of large aircraft include carrying large payloads for different kinds of missions, operating in all weather conditions, multi-mission capable, slow, redundant parts, not very maneuverable, and huge amounts of fuel onboard.

A. LARGE BODY AND NUMBER OF ENGINES

Aircraft produce signatures by reflecting signals or emitting noise and heat. The main sources of the RF and IR signatures are the large body and the number of engines. It is not practical to reduce the aircraft size or engines even though they cause the visual, acoustic, RF and IR signatures.

1. RCS Prediction and Aircraft Identification

The radar cross-section (RCS) of the target is the area that reflects the radar signals at a particular aspect and it is a function of:

- the target's geometry, reflectivity and directivity
- the radar's position relative to the target
- the frequency of the radar
- the polarization of the antenna
- σ = Projected cross section x Reflectivity x Directivity
- $\sigma = 4\pi \frac{P_s}{Pi}$
- P_s =Power per unit solid angle reflected by the target ($\frac{W}{sr} = W$).
- P_i =Power density or intensity reaching the target ($\frac{W}{m^2}$).

The RCS of a typical large aircraft is as shown in Figure 26. The RCS can reveal the vulnerabilities of aircraft at different frequencies. The radar range profile is a one-dimensional representation of an aircraft, obtained by the radar at

a particular aspect of the aircraft. These measurements are used for classifying the aircraft. In Figure 26, the radar returns from the scatters of an aircraft are projected on a one-dimensional line-of-sight representation.

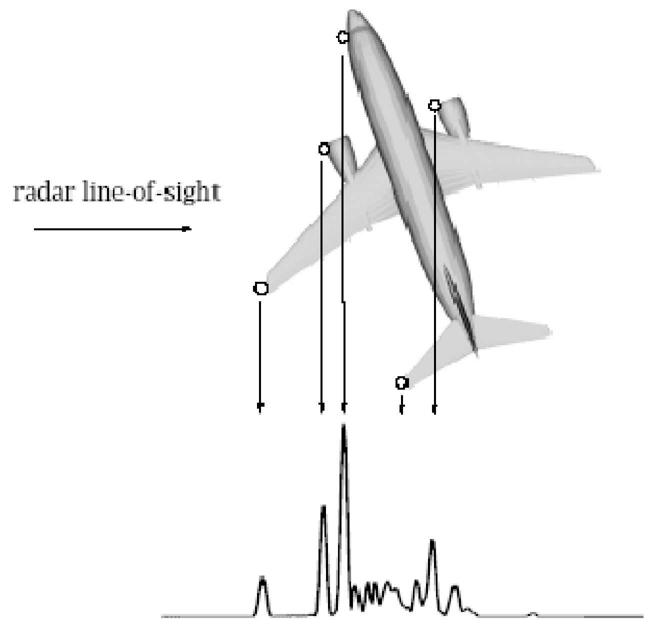

Figure 26. Example of a range profile of Boeing 737-500.[25]

In Figures 27 and 28, it is shown that a large aircraft's nose-on aspect can extend due to airborne radar and the reflections from the jet engines and their intake ducts. The compressor blades in jet engines, or propellers on propeller-driven aircraft, modulate the echo. When the radar antenna in the nose points in the direction of the viewing radar, the cross section can be larger.[26]

[25] Portegies Zwart, "Aircraft recognition from features extracted from measured and simulated radar range profiles," http://www.science.uva.nl/research/ias/alumni/ph.d.theses/theses/JorisPortegiesZwart.pdf, 2003, (accessed 20 March 2008).

[26] Merrill Skolnik, *Introduction to Radar Systems*. Boston: McGraw Hill, 2001, 58.

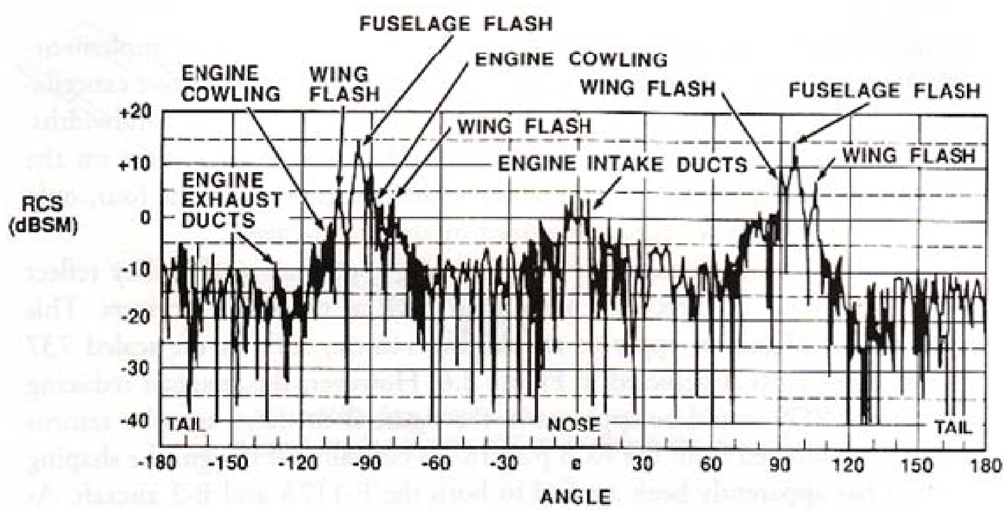

Figure 27. Measured backscatter (RCS) from a 1/15th scale model Boeing737.[27]

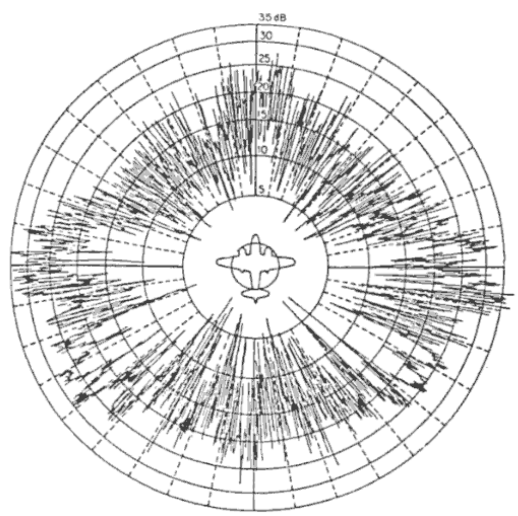

Figure 28. Radar principle.

[27] Curtis Schleher, *Electronic Warfare in the Information Age,* 511.

A small RCS contributes to the jamming effectiveness of a self-defense system. If the aircraft has a smaller RCS, then it needs less power to jam the radar. Moreover, the radar sensitivity should need to be increased to detect the same target.

P2-P1 = -39+10log(RCS)+20logF

2. IR Signature

The components of the infrared signature are shown in Figure 29. Sunlight is reflected and some of it is absorbed and reemitted by the airframe (skin emission). The exhaust plume expands, then becomes smaller and cools behind the aircraft; it also heats some parts of the airframe. Hot vents as well as landing and operating lights are also IR sources. The plume of the engine becomes cooler further away from the engine, and it makes a larger wavelength as the temperature of the plume decreases.

$$\lambda = \frac{2898}{T(K)} \mu m$$

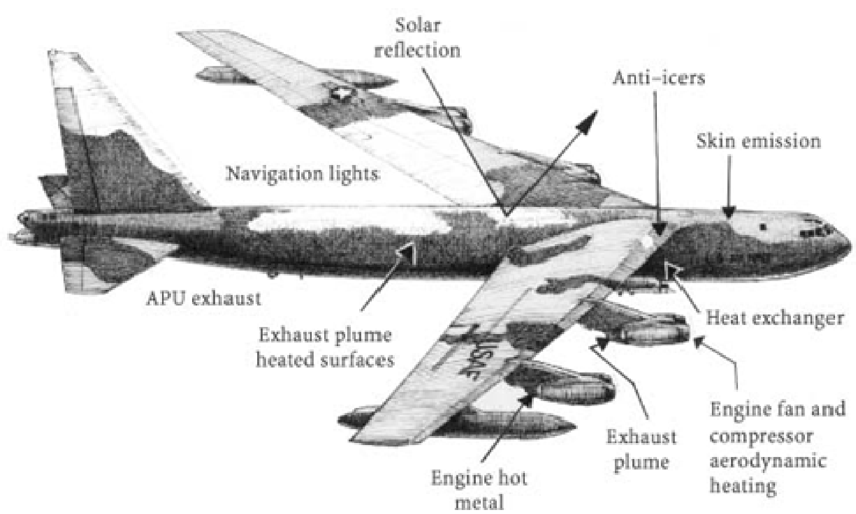

Figure 29. Components of IR signature.[28]

[28] Ball, 471.

The large IR signature produced by the engines enables missiles to detect, acquire, and track the target from longer distances. Throttle settings are also important.

Figure 30. Nose aspect IR imagery.[29]

Multiple engines have the disadvantage of revealing more IR sources and, even while jamming, they can be acquired by missiles. With a narrow field of view, a missile can capture several targets on a large aircraft. When a missile is jammed and diverted from its target, it should not reacquire another engine. Therefore, disruption can be a solution but the best one is destroying the missile's sensor.

Variations of an aircraft's spectral aspect angle are shown in Figure 31. From the tail aspect, tailpipe radiation is high. As the azimuth angle goes from 180° (tail) to 0° (nose), tailpipe radiation is obscured by the airframe and aerodynamic heating air intake ducts caused by the ram effect blunt surfaces and stagnation in the airflow over the airframe, becoming a more important factor contributing to the aircraft's signature.[30]

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[29] Gregory Czamecki, "Large aircraft vulnerability to MANPADs," Aircraft Survivability [Journal], Summer 2005, 10.

[30] Cooper.

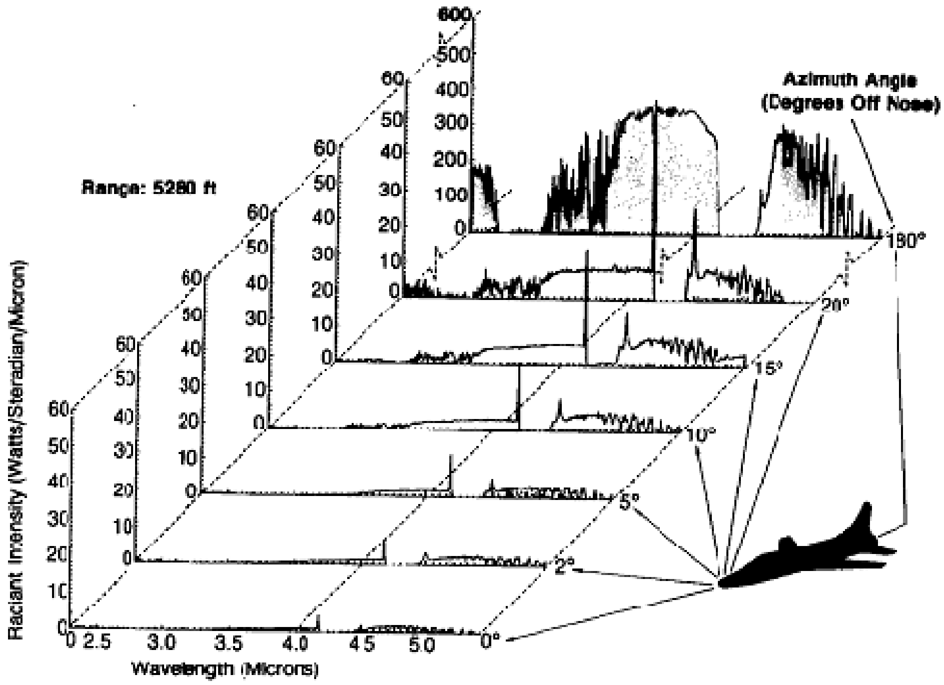


Figure 31. Variations of aircraft spectral signatures over aspect angle.[31]

Typical plume emissions are 3–5 micrometers and skin emissions are 8–12 micrometers.

The lethal footprint changes according to the IR performance of a missile.

[31] Accetta and Shumaker, 1993, 165.

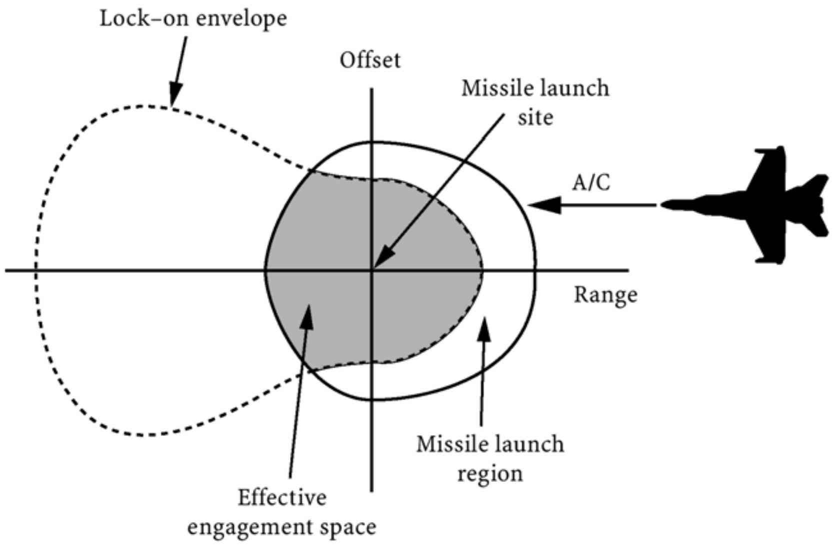


Figure 32. Lethal footprint for IR missile.[32]

The IR signature of a transportation aircraft engine can be calculated as follows.

If we assume the tailpipe has an effective emissivity of 0.9 and an exhaust temperature of 500°C, the radiance is:

$$N = \frac{\varepsilon\sigma T^4}{\pi} = \frac{0.9 \cdot 5.67 \cdot 10^{-12} \cdot (500+273)^4}{\pi} = 1.822 \frac{W}{cm^2 \cdot sr}$$

The radiant intensity of a single engine which has an exhaust radius of 20 cm is:

$$J_{engine} = N \cdot A = 1.822 \cdot (\pi \cdot 20^2) = 2289.6 \frac{W}{sr}$$

If the aircraft is at a distance where the individual engines cannot be resolved by the sensors, (in other words, if they are in the field of view of the infrared sensor) the radiant intensity of the aircraft becomes multiplied by the number of engines.

[32] Ball, 276.

$$J_{aircraft} = 2289.6 \cdot 2 = 4579.2 \frac{W}{sr}$$

26.6% of the radiant flux lies in the 3.2–4.8 μm region, so for the same engine effective radiant intensity is:

$$J_{engine} = 2289.6 \cdot 0.266 = 609 \frac{W}{sr}$$

Typical λ for peak spectral radiant exitance can be calculated with Wien's Displacement Law:

$$\lambda = \frac{2898}{T(K)} = \frac{2898}{773} = 3.75 \mu m$$

Aircraft Type	Intensity(Wsr^{-1})	
	2-3μm	3-5 μm
Rotary wing	10-100	100-300
Fixed wing(propeller)	20-200	200-500
Jet fighter	50-1,000	100-10,000
Jet transport	100-1,000	100-5,000

Table 12. Typical signature levels.[33]

Aerodynamic heating does not produce significant radiant emittance.

$$\mathrm{T} = \mathrm{T}_0 \left(1 + 0.164 \cdot \mathrm{M}^2\right) = 250\left(1 + 0.164 \cdot (0.4)^2\right) = 256.56K$$

$$W = \varepsilon \cdot \sigma \cdot \mathrm{T}^4 = 0.0221W$$

3. Aural Signature

The main source of noise in an aircraft is its engines. Turbojet engines generate low-frequency noise and can be aurally detected. High-frequency compressor noise makes little contribution to the noise signature. Turbojet engines suck in air, accelerate it and pressurize it, then push it back, producing

[33] Accetta and Shumaker, 1993, 297.

great thrust, with noise. Another source of noise is airflow separation, which causes turbulence and noise in the engine. The engine nozzle is also a source of noise emission. Finally, as the aircraft flies through the air, the surface of the aircraft creates noise.

4. Laser

Laser illumination on the aircraft can be either direct or indirect (scattered) radiation. The divergence of the laser beam is smaller than other types of propagated waves. Therefore, it illuminates a small area on the aircraft. As the aircraft size becomes larger, the number of laser warning receiver sensors must be increased.

B. FLIGHT PROFILES

Large aircraft usually fly above 15,000 feet, which means they are usually free from the MANPAD threat. A typical flight consists of three parts: takeoff and climb, en route, and descent and landing.

The typical flight path of a large aircraft is shown in Figure 33. Different kinds of SAMs threaten the different phases of flight. Vulnerabilities change according to the mission types and components.

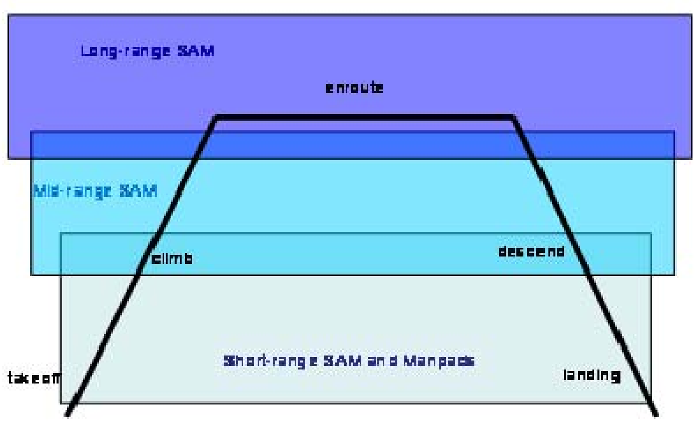


Figure 33. Flight phases and threats.

C. MISSION DIFFERENCES

Military aircraft operate in a highly threatened environment. When the mission dictates, they operate at less than 15,000 feet for airborne delivery, search and rescue, and special operations. Those missions might be over hilly terrain, desert, or dense vegetation and in all weather conditions, such as sunny, snowy, or rainy. Large military aircraft, such as tankers, transports, bombers, and AWACS, are strategic air power assets. Each of them accomplishes its mission in or near hostile fire. Although these large aircraft have redundant systems for emergencies, it is the tons of fuel and the size of the fuel tanks onboard which makes them most vulnerable.

Figure 34. Missile in chase.[34]

[34] Rick Raesly, *Defensive Systems Capability Requirements*, 2007.

IV. DETECTION OF THREATS (WARNING SYSTEMS)

The best countermeasure is to avoid the threat. To avoid the threat, it must be detected. Warning systems help the aircrew to take effective evasive action and to use countermeasures against threats. In order to do so, they must be provided with accurate and timely threat data.

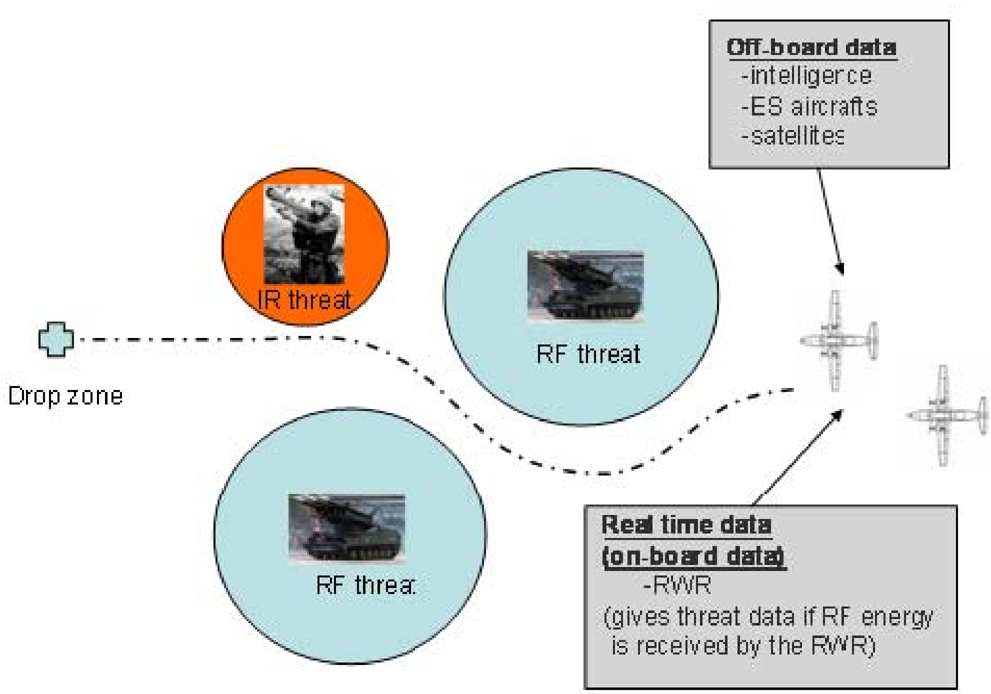


Figure 35. Threat avoidance.

Threat avoidance can be supplied by two means. First, off-board data might come from intelligence and reconnaissance means, such as satellite data or signals intelligence (SIGINT), which can include electronic intelligence (ELINT) and communications intelligence (COMINT). But these may not reflect the real-time situation with off-board means. Second, data from onboard radar warning receivers (RWRs) are used to complete the mission safely. RWR is limited to the

RF portion of the electromagnetic spectrum. Therefore, if the missile employs an IR seeker, then RWR is unable to detect it. The flying platform needs a suite or combination of sensor systems. The suite should create a continuously updated electronic order of battle and evaluation of threats. If a missile is fired, then the aircrew needs to know a missile is launched and from what direction.

Detection range is the range between aircraft and missile at time of launch of the missile and it is an important factor to initiate the countermeasures. The required minimum detection range is related to

- minimum warning time
- the speed of aircraft
- the speed of the missile
- the direction of attack

For example, a C-130 or C-160 operating at Mach 0.4 (240 knots) engaged by a Mach 2 missile has a closure rate of Mach 2.4 for head-on and Mach 1.6 tail. It must have a detection range of at least 2 nm for head-on and 1.33 nm for a tail engagement if a minimum of 5 seconds warning time is required to initiate the countermeasures effectively. Increasing the missile speed increases the closure rate, so it requires increasing the detection range.

Spatial coverage should be as in Figure 36. There should not be blind sectors. However, possible blind spots are the sides of aircraft, which are far away from antenna's boresight.

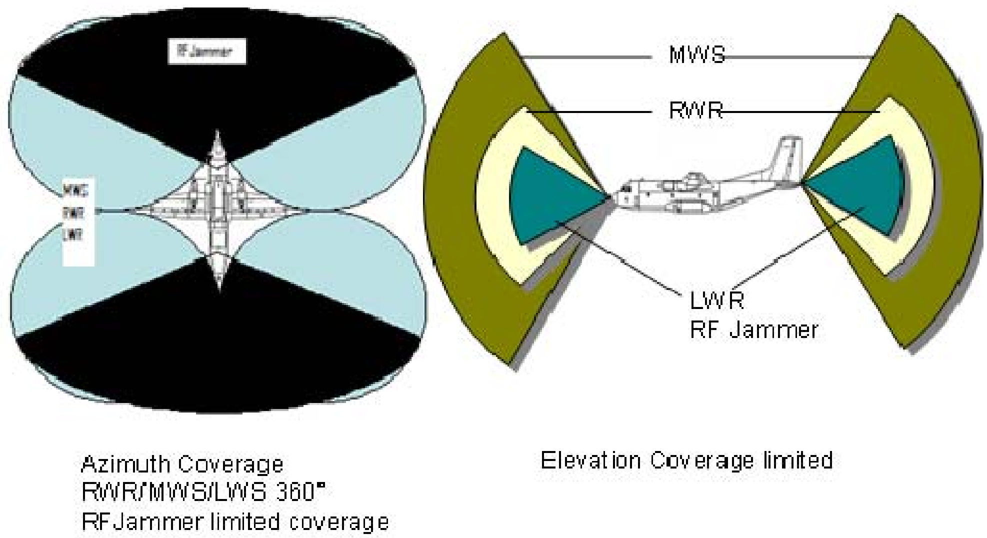


Figure 36. Spatial coverage of warning systems.

False alarms are one of the biggest problems with warning systems. If the countermeasure system employs flares or other one-time usable expendables, false alarms may diminish their already limited number. Moreover, by initiating expendable countermeasures, such as flares, the enemy can become aware of an aircraft's presence visually. Therefore, the aircraft's susceptibility increases.

Reducing the false alarm rates is the solution, which can be accomplished by increasing the threshold level. However, using this method lowers false alarms at the expense of missed detections. The probability of detection is increased by incrementally reducing the threshold level; on the other hand, it increases the false alarm rate. Determining an optimum threshold level is an ongoing challenge. In Figure 37, the classification of threat warning systems is shown with examples.

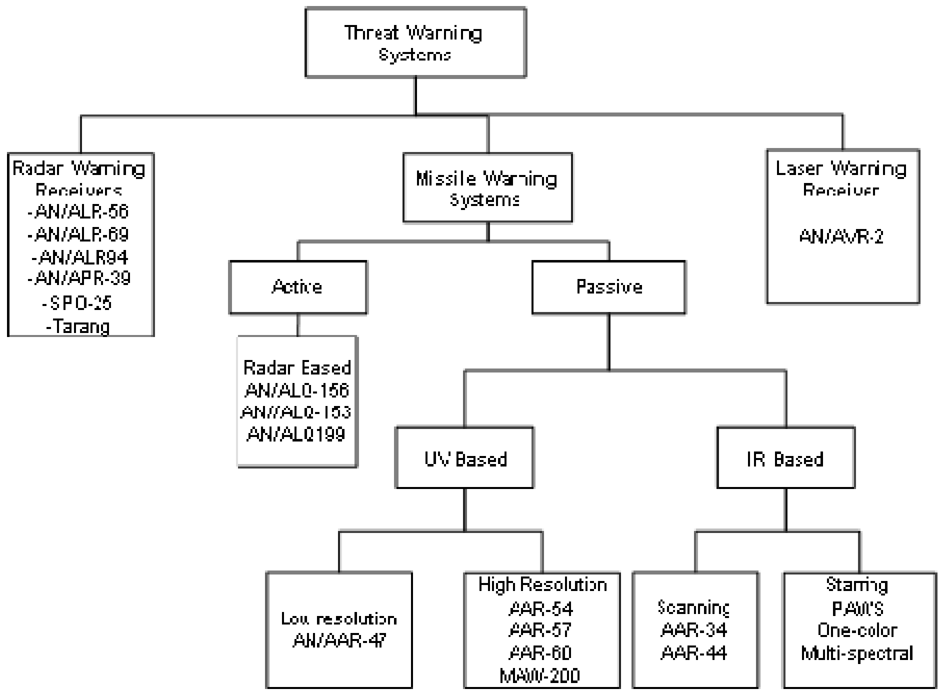


Figure 37. Threat warning systems.

A. RADAR WARNING RECEIVER (RWR)

1. General System Principle

In order to have advance notice of a missile attack or even to detect the presence of a radar, the aircraft may carry RWRs. The pilot can take evasive action to defeat the threat based on RWR indications.

An RWR is a receiver designed to monitor the RF environment continuously and alert crews about a radar threat to an aircraft. There are millions of signals in today's world. However, RWRs basically intercept the mainlobe radiations of radars. Mainlobe detection means the RWR will detect systems that are pointing at the aircraft and not indications from sidelobes when the radar is looking somewhere else. RWRs have very capable signal-processing devices in order to identify the threat signal among the high-density signal environment. When it receives a signal, it compares the signal with its large

database of threat features, such as pulsewidth, frequency, and pulse repetition interval. If the signals match, then the RWR gives a visual, audio, or both, warning according to that threat type. As the crew is aware of the threat, they take precautions to defeat the threat. It is vital to keep the threat libraries updated and accurate for identification emitters and weapon systems because, when a new weapon is developed, it has its own characteristics. If the data are not in the threat library, it cannot be matched; therefore, it appears as an unknown threat.

The basic duty of an RWR is to find the range, bearing, and identity of any radar that illuminates the aircraft with the mainlobe. The pulse train is examined to find that information. The first step is interleaving, which means to separate the pulse train received from a specific radar from the others. The second step is to predict the radar type by using some parameters like pulsewidth, pulse repetition frequency (PRF), and frequency band to differentiate one type of radar from others. The third step is to find the direction of arrival by forming an amplitude monopulse measurement using two adjacent quadrant antennas.

In Figure 38, the circles represent each of the four RWR antennas' patterns. On the right upper side there is a threat pulsed radar. As the main beam rotates, it will only be received by Antenna #1 and Antenna #2. By comparing the amplitude of the received signals, the angle of arrival can be obtained. Since RWRs do not have very sensitive receivers, they only receive the main beam of the threat. Once the RWR processor identifies the threat, then, by means of the effective radiated power (ERP) of the radar and one-way link equation, the range to the emitter is calculated.

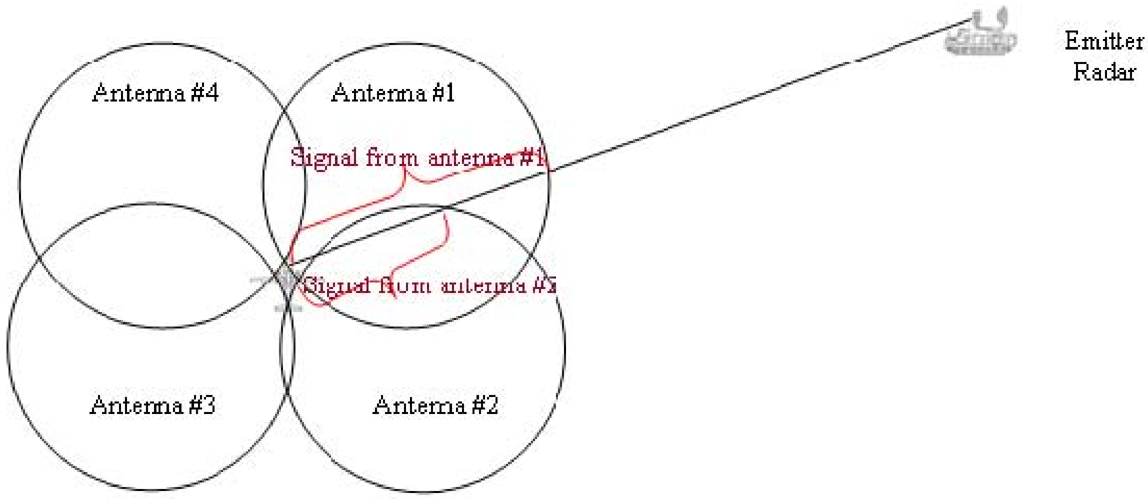


Figure 38. RWR antenna patterns.

Saturation effects due to high-pulse signal densities negatively affect RWRs and their signal processors, because they increase the total processing time since each signal must be classified. A shadow time is a period of time in which an incident pulse is lost because the processing time of the receiver is greater than the interpulse arrival time. As the processing capability improves. the shadow time decreases. All RWRs have a shadow time in which they are susceptible to losing a signal.

RWRs can detect the type, location and operation mode of the threat. Threat operating modes are search, tracking and launch. As indicated by the red area of Figure 39, typical RWRs cover the frequency range 0.5 to 40 gigahertz of the electromagnetic spectrum. Typical missile guidance radars employ 8–12 gigahertz, which means X bands, shown in blue in Figure 39.

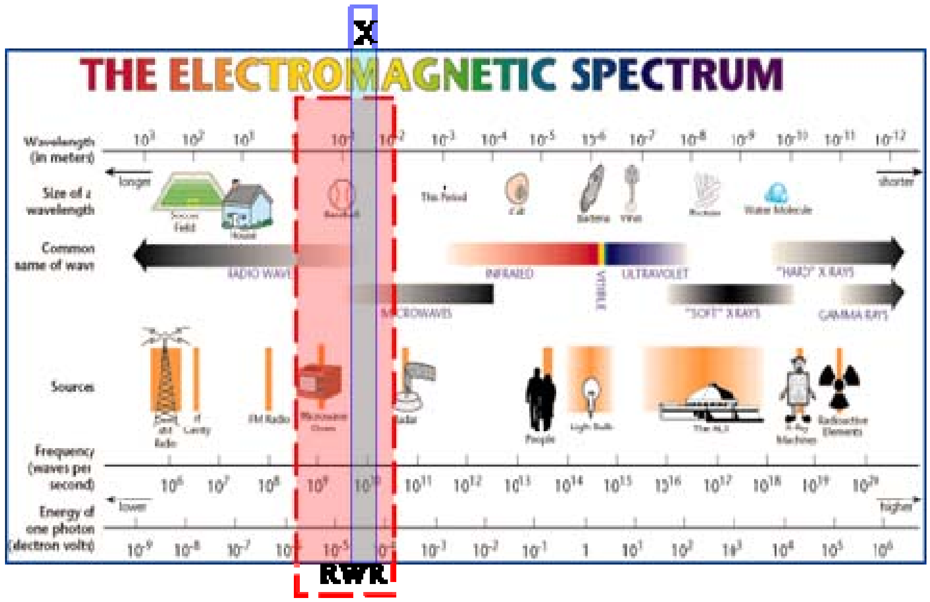


Figure 39. Typical RWR frequency[35].

2. RWR System Components

RWR system components are the antenna, receiver, signal processor, and display.

[35] EM Spectrum, Available from http://www.electro-optical.com/html/bb_rad/emspect.asp (accessed 14 February 2008).

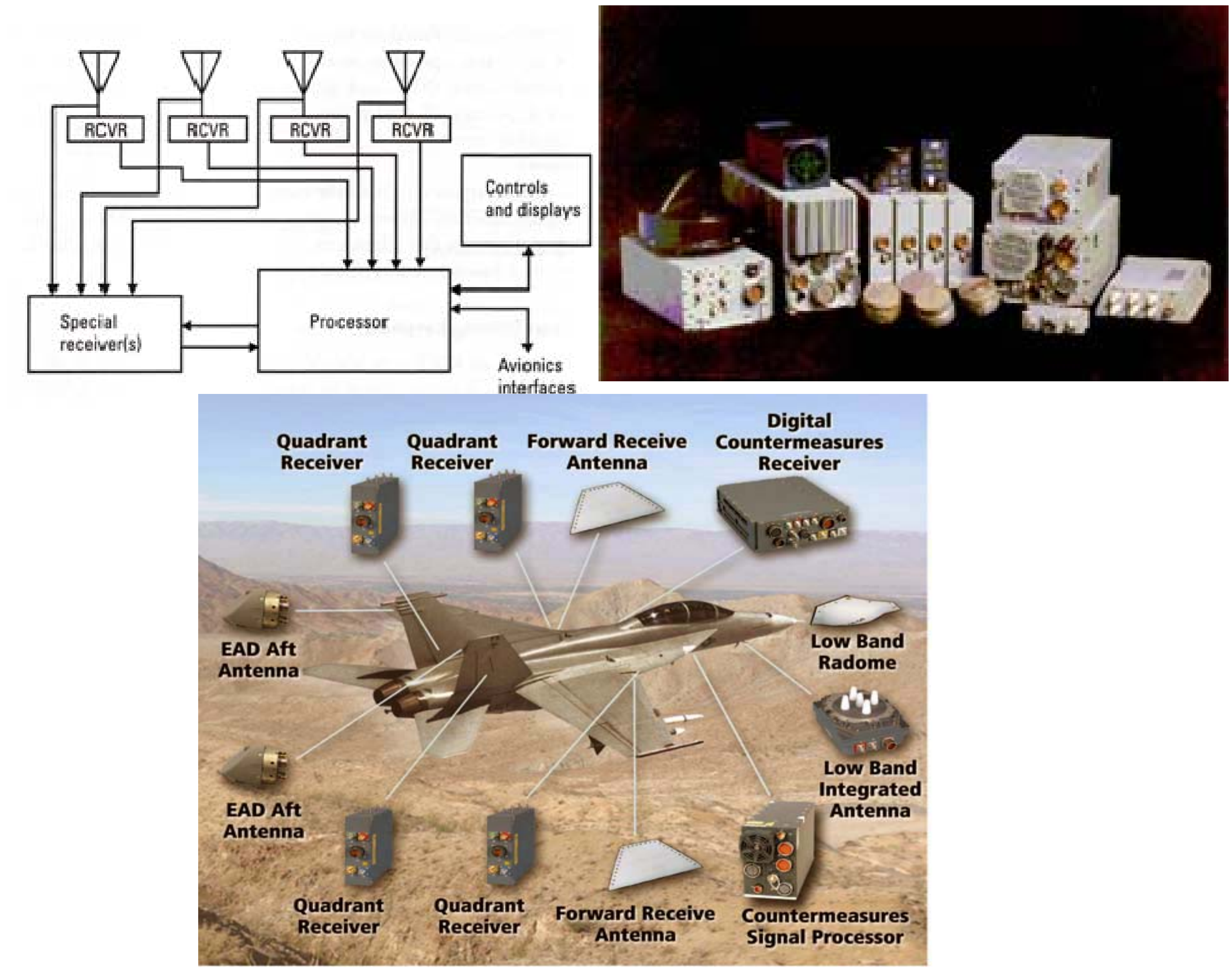


Figure 40. RWR System Components.[36]

RWR antennas are symmetrically located and deflected 15° from the yaw axis to insure 360° coverage. The pitch angle is +1/2° to -45°.

[36] David Adamy, *EW 102: A Second Course in Electronic Warfare,* Artech House Radar Library, (Artech House: Boston), 2004, 75.

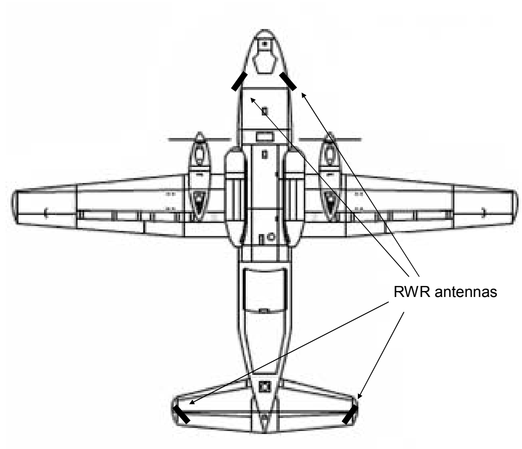


Figure 41. Typical RWR antenna placement.

The receivers include crystal video receivers to receive pulses over a wide frequency range. In modern RWRs, narrow-band receivers are also included to process CW and pulse-Doppler radar signals.

3. Receiver and Sensitivity of RWR

The lowest signal level that can be detected meaningfully by a receiver is called sensitivity. Before entering the firing range of a threat, an RWR must detect and warn the aircrew about the presence of a threat. Otherwise, it is probable that some hostile weapons might hit the target. In this regard, sensitivity is important. If the RWR is highly sensitive, it can detect low power signals at longer ranges.

Sensitivity equals the sum of thermal noise in the receiver, noise figure, and signal-to-noise ratio.

$$Sensitivity = kTB + NF + SNR$$

kTB is the thermal noise in the receiver.

$$kTB = -114dBm + 10\log(\frac{BW}{10^6})$$

$$BW = \frac{1}{\tau}$$

In an RWR's case typical values are

Radar pulsewidth (τ)=10^{-6} seconds

Signal-to-noise ratio=SNR=13dB

Noise figure=NF=5dB

Detection range of radar:
Transmitted power= Pt =100kW = 80dBm

Gain of transmitter=Gt=30dB

Frequency=f=10 GHz

Radar Cross Section=RCS=variable between 10-100 m^2

Radar Range Equation:

$$R_{\max} = \left(\frac{P_t . G^2 . \lambda^2 . \sigma}{(4\pi)^3 S_{\min}} \right)^{\frac{1}{4}}$$

Another formula, in dB form, to calculate the range is:

40log(d)=-103+80dBm+2(30)dB-20log(10000)dB+10log(10)dB-(-96dBm)

=63dB

d=37600meters

An RWR can see the main beam of the threat radar when it is focused on the aircraft. Since threats can come from any direction, the RWR uses wide beamwidth to increase the probability of detection. RWR antennas also have wide frequency coverage. Therefore, these two limitations lead RWR design into low gain. RWR bandwidth must be wide enough to detect narrow pulse widths. Typical radar bandwidths are 4 GHz and RWR video bandwidth is 10–20 MHz.

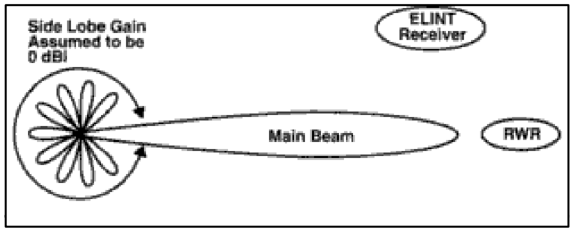


Figure 42. RWR antenna patterns.[37]

$$BW_{eff} = \sqrt{2 \cdot B_{RF} \cdot B_{VID}}$$

Received power density at the target (RWR) is

$$P_r = \frac{P_t \cdot G}{4\pi R^2}$$

Pr=Pt+Gm-32-20log(F)-20log(d)+Gr-Sensitivity

Typical RWR antennas have 0-dBi peak gain at 10 GHz for any direction of arrival.

Analog circuits have big error sources, such as limitations, calibration, and maintenance. However, digital signal processing-enabled stability means no errors caused by temperature differences, no need for frequent calibration, and easy integration with the computer systems and other onboard systems.

4. Characteristics of RWRs and their Capabilities

An RWR fingerprints a threat radar by frequency, pulsewidth, PRF patterns, missile guidance, scan pattern, power density, and angle of arrival (AOA).

These fingerprints identify and locate the system that generates them. Threat radars have short pulsewidths. Threat radars also have some kind of scan method for auto tracking, particular scan resolution, and PRF patterns, like jittered, staggered, or a combination of them, which helps to resolve the

[37] Adamy, 2004, 53.

ambiguities. Generally, five of these fingerprints can resolve the range ambiguities. However, many threats have close to the same fingerprint sets. Therefore, an RWR uses additional parameters: transmitter power and beamwidth.

An azimuth can be obtained from a direction-finding (DF) antenna and an approximate range can be determined from received power level. With this information, the proper symbols are displayed on the RWR:

Due to the narrowing of the video bandwidth, the sensitivity of crystal video receivers is an order of -40 dBm for pulsed signals and -50 dBm for a CW signal. These RWRs are good against high-powered, low-repetition pulsed weapon systems and CW systems. However, RWRs have difficulties in sorting and grouping pulses, which are transmitted by high-repetition rate radars.

Most RWRs cannot detect low-probability-of-intercept (LPI) radars, also known as “quiet” radars, because extraction of those signals from the noise requires digital processing.

Modern RWRs, which utilize a digital receiver (DRX), have the advantage of digital processing in terms of reproducibility, stability, flexibility, and programmability of signals. Therefore, those new achievements led to detection of CW/ICW emitters, detection of LPI radar, and modulation on-pulse (MOP) analysis for identification and fingerprinting.[38]

In conclusion, an RWR improves situational awareness and can detect the RF threat before it launches. Some RWR types are listed below.

---

[38] Neri, 2001, 324.

AN/ALR-69	(LORAL)
Description:	The RWR system detects, identifies, processes and displays airborne interceptor (AI), surface-to-air missile (SAM) and anti-aircraft artillery (AAA) weapon systems.
Features	The Advanced Crystal Video Receiver [ACVR] consist of radio frequency (RF) Triplexer, Extended Range Dual Log Video Amplifier (ERDLVA) and Logic Board. It will provide increased receiver sensitivity, increased dynamic range, and increased pulse density and signal processing capability. The ACVR will reduce maintenance costs through improved reliability and maintainability and enhanced Built-In-Test (BIT).
AN/ALR-94	(BAE Systems)
Features	The AN/ALR-94 is a passive receiver system capable of detecting the radar signals in the environment. Composed of more than 30 antennae smoothly blended into the wings and fuselage, it is described by the former head of the F-22 program at Lockheed Martin as "the most technically complex piece of equipment on the aircraft." With greater range (250+ nm) than the radar, it enables the F-22 to limit its own radar emission, which might otherwise compromise its stealth. As the target approaches, AN/ALR-94 can cue the AN/APG-77 radar to keep track of its motion with a narrow beam, which can be as focused as 2° by 2° in azimuth and elevation.

Table 13. Some RWR types.

B. MISSILE WARNING SYSTEMS

RWRs are designed to detect hostile fire-control radars or missiles that employ active radar seekers onboard. An RWR is not enough to detect missile tracking. When a missile is fired, and does not employ RF energy for guidance, then the aircrew must rely on visual acquisition, which is extremely difficult.

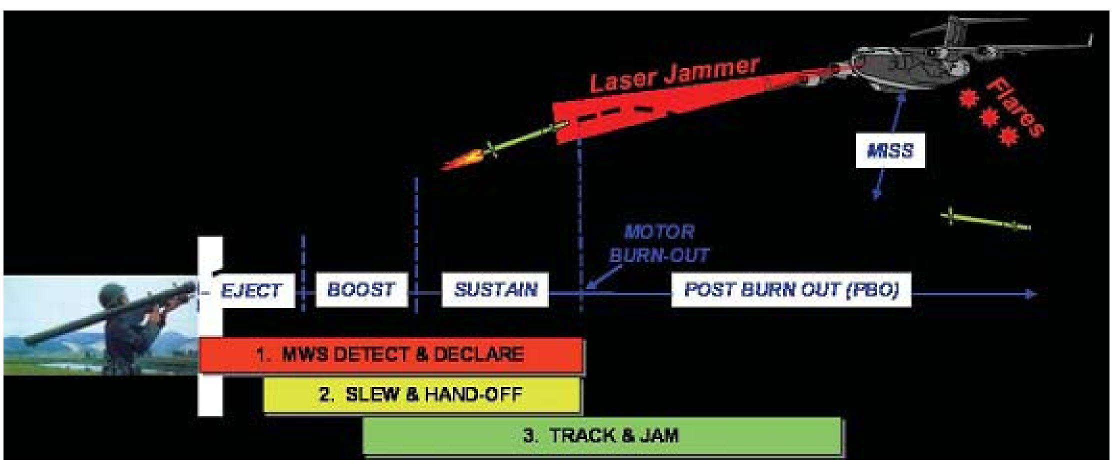


Figure 43. Detection phases.[39]

39 Raesly, 2007.

A missile warning system (MWS) can be either active or passive. Active warning systems transmit and receive reflected RF signals. Active missile approach warners have small CW or pulse-Doppler radars that are able to detect fast-approaching targets with a small RCS, which is probably a missile.[40] The advantages of an active radar warning system are their long range, all-weather capability, and low false alarm rate. On the other hand, they are susceptible to being jammed. They reveal their own signature, which can be detected by other RWR platforms, and they can be targeted by an anti-radiation missile.

Passive warning systems only monitor for either IR or UV signature. A passive MWS cannot detect a radar that is searching or tracking. Missile approach warners detect the launch or approach of a missile, providing that the UV or IR emission is within the FOV of the sensors of the warning systems.

Passive warning systems, which have IR or UV sensors, can detect the threat's propulsion system. Basically, a UV sensor can detect the flame of a very hot booster rocket or afterburner; an IR sensor can detect a jet engine's exhaust or a rocket plume. Longwave IR can even detect the hot leading edges of an aircraft or subsonic missiles. They can give very accurate angular data. But they are very dependent on atmospheric transmittance and are vulnerable to inclement weather. In the battlespace, fires, sun glint, lightning, gun flashes, and explosions can be a challenging problem for missile warning receivers, which are steady optical sources. They are more susceptible to false alarms and the range must be estimated based on signal strength.

1. Radar-Based Active Missile Warning System

This system is different from RWRs because it uses active radar to detect incoming threats. Radar's capabilities are used for all-weather, accurate missile range estimates and impact times derived from those data. However, the transmitting signal also discloses the aircraft's presence. The very small RCS of

[40] Schleher, 451.

the missile and the multipath signal caused by the reflected signals from different obstacles make it hard to detect and sometimes produces false alarms. At low altitudes, strong ground clutter can be observed. Other problems can be antenna coverage and minimum closure rate. Performance does not depend on weather. If a radar-based active missile warning system is employed, then there may be no need for an RWR. Some radar-based active missile warning systems are described in Table 14.

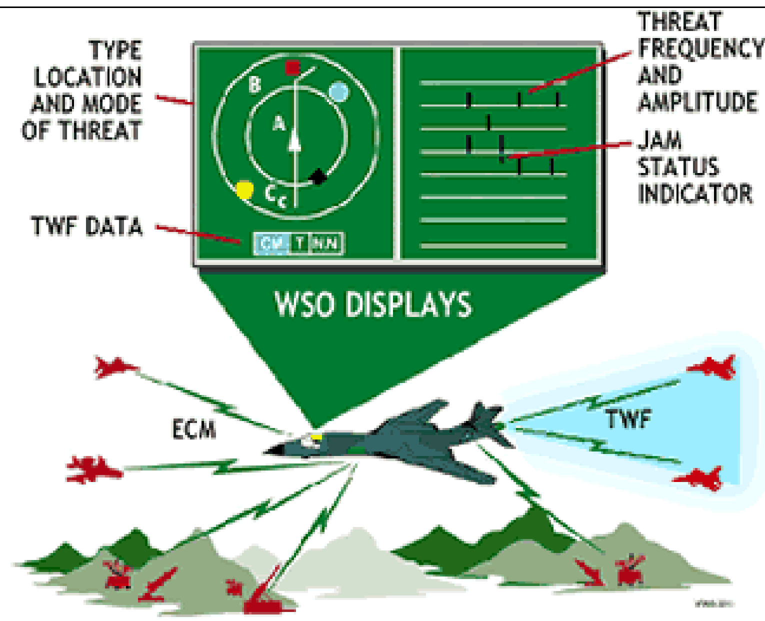
AN/ALQ-156(V)	(BAE SYSTEMS)
Description:	Missile Warning System
Features	360-degree pulse Doppler radar missile detector that illuminates an incoming missile, detects the RF reflection, and measures the missile's range and velocity to accurately determine time-to-go and provide the optimum triggering of an expendable to protect the host platform.
AN/ALQ-161	AIL Systems Inc.
Description:	Tail Warning Function (TWF) to detect incoming missiles from the aft sector.
Features	 The Tail Warning Function provides a Pulsed Doppler radar function to detect any missile threatening the bomber from the aft sector. The system provides 360-degree receive and jamming coverage against a large number of simultaneous threats,

Table 14. Some radar-based active missile warning systems.

2. Passive Missile Warning Receivers

In missile warning receivers, the detection range is always greater than the declaration range, which is the range at which the detected signal is classified as a threat. This is due to the processing time for deciding whether the detected target is a real threat or not. This interval for processing data is called latency time.[41] For missile detection, the important criteria are observables, propagation, background and clutter, and signal detection.

a. Ultraviolet Warning Systems

An ultraviolet missile warning system employs UV-based detectors. UV-based missile approach warning systems are simpler and have short ranges. Their sensors are small and do not require cooling. They do not have visible moisture problems. In the atmosphere, the thick layer of ozone blocks solar UV radiation. Also, there are low natural background and clutter levels that can cause false alarms because solar-blind UV is the 250–280 nanometer band, where solar radiation is completely absorbed by the atmospheric ozone and enables a clear background for missile plume detection. The chemiluminescence between carbon monoxide (CO) and oxygen (O) is the dominant source of UV emission in the solar blind range, and scattering in this plume resolves the problem for head-on approach.

On the other hand, they have higher altitude and urban pollution restrictions caused by ozone limitations. Ozone concentration in industrial areas reaches high values in summer (atmospheric scattering and absorption). UV's short range is caused by the ozone, which absorbs the UV radiation of the target. Halogen lamps, fires, sparks, welders, etc., can cause false alarms. After the missile's fuel is expended, it cannot be tracked by UV due to lack of signature. In general, UV systems have been widely used for platforms that fly slow and at low altitude.

41 Accetta and Shumaker, 1993, 16.

They are low in cost due to their simplicity and they have minimal background clutter problems. It is a mature technology.

High-thrust propellants can be detected easily since they emit strong UV, but low-visibility propellants for the missiles and post-burnout detection are insufficient aspects of UV-based warning systems.

Some passive missile warning systems are described in Table 15.

AN /AAR -54(V)	(Northrop Grumman)
Description:	Passively detects UV energy from the missile's exhaust plume, track multiple sources, provides threat information to the countermeasure system.
MAW-300	Saab
Features	A unique optical design, incorporating state-of-the-art filter technology, with purpose-built image-intensifier tubes and photon-counting focal-plane array processors ensures high sensitivity, which equates to long detection range. Each sensor is served by a dedicated high performance digital signal processor, making use of highly pipelined command execution and parallel processing.
SBUV	Detects the UV radiation of the approaching missile and hands over its coordinates to the fine-tracker and jamming system.

Table 15. Some passive missile warning systems.

In Figure 44, a mortar launch test demonstrated the use of UV-based detectors. The biggest signature is the launch of a missile.

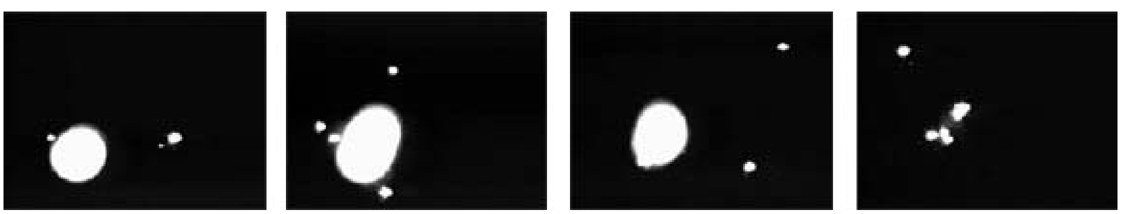


Figure 44. Images over time during launch.[42]

b. IR-Based Warning Systems

A missile plume has a much higher IR signature than UV signature because the IR content of the missile plume is larger. In the IR band (3–5

[42] SBUV, "Missile Approach Warning Sensor," http://www.sbuv.com/MissileWarning/index.html (accessed 20 March 2008).

micrometers) the atmospheric absorption is less than in the UV band. IR-based warning systems are more complex, but they have greater range capability. They can detect plume emissions and hot aircraft parts as well. They have the potential for post-burnout tracking. However, they have visible moisture limitations.

Numerous other IR sources in this band can increase the false alarm rate. Sophisticated processing is required to remove clutter. To decrease the need for discriminative processing, two-color or multi-color detectors are developed. The biggest problem with IR detectors is the need for cooling to reduce thermal noise. The cooling devices make the systems more likely to malfunction and make the system bulky, vulnerable, costly, and weighty.

Signatures	IR(W/sr)	UV(mW/sr)	Time(seconds)
Boost	100	10	1.5
Sustain	10	3	1.5-7.1
PBO(post-burn-out)	0.1	0	7.1

Table 16. Example of a missile signature.[43]

The characteristic emissions of today's propulsion technology, listed above, will change in future-generation missiles, which will utilize new-generation propellants to release fewer signatures.

For a missile approach warning system, the observation angle is important. If the image has a steady perspective, then it becomes easier to detect. It is easier to detect a missile that employs a proportional guidance system since it is seen from a constant angle by the target. On the other hand, for the command line-of-sight schemes, it is difficult to detect a missile due to the fixed position along with the background clutter.

[43] Cooper.

C. LASER WARNING RECEIVERS

Each laser type has its own properties, like wavelength, PRF or pulsewidth. Laser warning receivers (LWRs) have the same principles as crystal video RWR. It compromises receiving optics, optical filters, detector arrays, receiving systems, and output. Receiving optics collect the laser energy. The optical filters reject energy seen as non-laser or at all other wavelengths other than the interested wavelengths. The accepted laser radiation, which comes from the filter, is focused onto the detector or scanned across an array of detectors. The output consists of electrical signals and they show the modulation characteristic of the illuminating laser. But deriving the illuminating laser source is different than in RWRs. A laser beam illuminates a small area on the target. Laser radiation may be detected from reflections from the airframe or scatter from the atmosphere. Any directional information would have little relevance to the true detection of the laser. The atmosphere distorts the wavefront and introduces large errors in direction measurements. There are techniques for helping LWRs to overcome propagation and refraction problems. Four indirect detectors give a protected area of 1.6 m diameter and direct detector 360 +10 -45 elevation.[44] But they do not give a precise angle of arrival. There are examples of direct and indirect LWR sensors in Figure 45.

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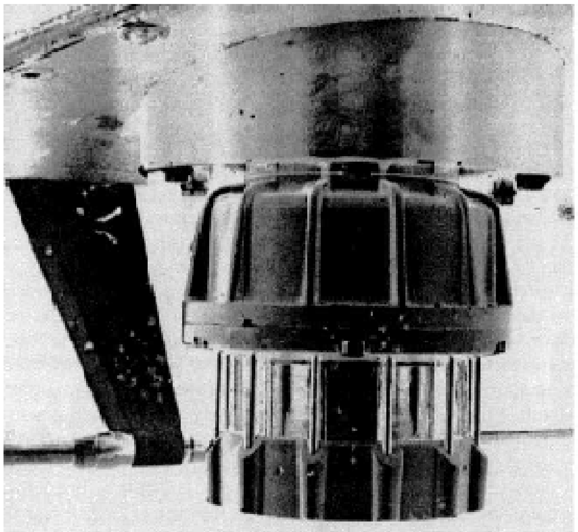
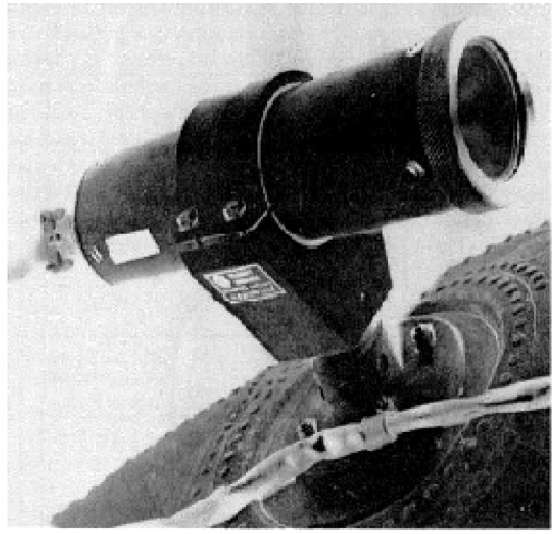
[44] J. P. R. Browne and M. T. Thurbon, *Electronic Warfare,* 1998 (Brassey's Inc.: London; Washington), 221.



Direct LWR sensor



Indirect LWR sensor

Figure 45. Direct and indirect LWR sensors.[45]

As in Figure 46, a 2-D array of detectors can give precise AOA information.

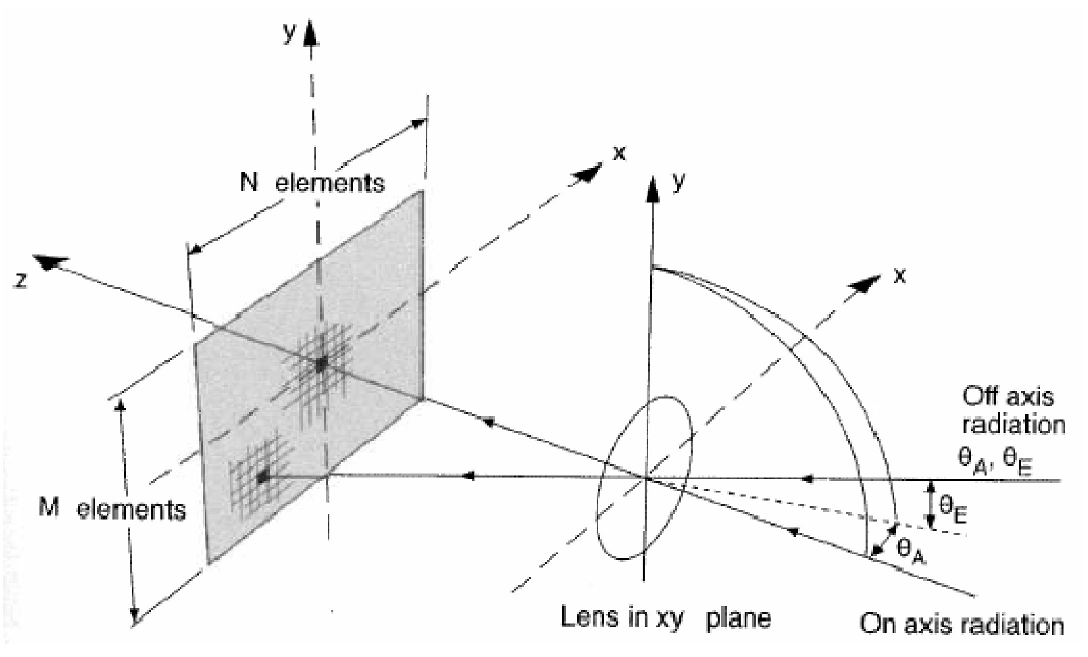


Figure 46. 2-D array detectors.[46]

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[45] Browne and Thurbon, 220.

LWRs must cover the proper waveband and be able to identify the missile characteristics. The basic steps of LWR are detection of signal, discrimination of the real signal from false signals, characterization of the laser, and localization of the source.[47]

Signal detection is related to the system's sensitivity and is usually limited by solar shot noise and Johnson noise in the visible and near-IR regime and by detector/thermal noise in the mid- and far-infrared. If the receiver sensitivity is high, it can destroy the receiver or cause a saturation effect that results in incorrect signal characterization.

False Alarm Problems	MWR	LWR
Sun glint, lightning, gun flashes, explosions		Rejected by Coherent detection techniques
Steady optical sources (battlespace fires)	Still a problem	Rejected by transient-oriented circuitry or typical LWR
White noise-generated		

Table 17. False alarms.

Characterization of a threat laser by an LWR can be accomplished roughly by measuring laser wavelength, intensity duration and PRF. Weapon lasers are at specific wavelengths and usually have long-duration pulses. Since LWRs work coherently with the laser countermeasure transmitters, they must acquire pulse repetition rate and /or pulse interval more accurately.[48]

46 Browne and Thurbon, 220.

47 Accetta and Shumaker, 16.

48 Ibid., 17.

An LWR can localize the threat by first determining whether it is coming directly or not. If the photons of the incident beam are scattered by target or the atmosphere, these secondary scatter/reflection intercepts can cause misleading directional data and it is very difficult to extract the correct threat location. For an LWR, a few degrees may be adequate to localize the threat, as in RWR. However, for directional countermeasures, directional accuracy must be better, because effective jamming can be done with a solid angle, which illuminates the seeker.

Laser wavelength is primarily determined by laser material with a variety of individual laser ‘lines’ possible from any individual material. Mostly, military lasers are continuous wave, long-pulse, or short-pulse multimode devices and they radiate an unpolarized beam.

“The continuous wave lasers (example: gallium arsenide semiconductor lasers and CO2 gas lasers) are usually modulated at high rates and are used in applications such as communication or missile guidance, in which they can carry large amounts of information.”[49]

1. Propagation

Atmospheric scatter and atmospheric scintillation are major concerns. Throughout the visual and into the mid-IR spectral region, the dominant source of near-earth and low-altitude attenuation is the aerosol-scattering component.

The laser beam may not directly strike the LWR and when it is not directly incident, it usually passes nearby. Therefore, detection of light scattered from the adjacent air is a major aspect of LWR design.

Basically, there are two scatter sources: the adjacent atmosphere and the target platform. In order to view the scatter from a portion of one’s own platform, the LWR must be positioned properly.

[49] Accetta and Shumaker, 55.

2. Backgrounds and Clutter

Potential false alarms may be caused by:[50]

- Scene clutter resulting from steady-state solar reflectance and thermal self emission
- Sun glint
- Battlefield sources (gun flash, fires, etc.)
- Lightning
- Electromagnetic interference
- Cosmic rays.

Those false alarm sources can be eliminated by high coherency, pulse rise time, pulse energy, sensitivity characteristics of laser radiation. The typical LWR wavelength band is 0.5-1.6 µm.

Some LWRs are described in Table 18.

LWS 300	Saab
Features	The LWS provides threat classification and direction finding (DF) indication of laser rangefinders, designators and lasers used for missile guidance purposes and dazzler lasers. The system is designed to be stand-alone or to interface with an existing on-board RWR/ESM host-system via the EW Controller for data processing and interfacing to the host EW system. A priority interface to the countermeasures system is available for the activation of countermeasures. Broad coverage of the laser spectrum ensures detection of most known current threats. The sensitivities of the LWS-300 sensor has been carefully chosen to provide warning of laser threats at ranges generally 1,5 times the threats engagement range. High sensitivity with optimised installation ensures the detection of lasers targeting any part of the platform.
301-M	Goodrich
Description:	The 301-M LWR detects, prioritizes in order of lethality, and characterizes Beamrider, Designator, and Rangefinder threats.
AN/AVR-2	
Description:	A passive laser warning system, which receives, processes and displays threat information resulting from aircraft illumination by lasers.
Features:	Provides advance warning of laser energy directed against the aircraft, including both laser range finders and laser guidance systems, enabling the aircrew to take evasive action. The Laser Detecting Set detects engagement by laser-aided weapons and delivers sufficient warning to the aircrew to allow evasive lifesaving action to be taken. Consisting of four sensor units and a central interface unit, the system detects, identifies, and characterizes laser-aided weapons 360 degrees around and +/- 45 degrees in elevation about the aircraft.

Table 18. Some LWRs.

50 Accetta and Shumaker, 55.

D. CONCLUSION

RF missiles have a greater target range than IR missiles, whose effectiveness is severely degraded by the atmosphere. But RF is a mature technology and is becoming more complex and expensive. Passive missile warning systems usually give the alarm when they sense the flash of the launch. UV sensors are more effective at low altitudes whereas IR sensors are effective at higher altitudes. UV radiation is usually man-made so it rarely occurs in nature. However, IR radiation is more frequent, which means that more time has to be spent distinguishing threats from clutter. A laser warning system warns that the aircraft has been illuminated by a range-finding or targeting laser. They have a limited range but are very effective and precise.

The important thing is to be aware of the threat and from where it comes from.

V. THE METHODS OF COUNTERING

There are three approaches to countering a SAM threat. First, there are the actions taken by the targeted aircraft through maneuver or design. The second is the atmospheric environment between the plane and the missile where expendables, towed decoys, and the physical characteristics of the environment interact. Finally, there is the missile itself. In Figure 47, each solution pertaining to that subject is shown. The target produces or reflects signatures; the atmosphere enables the propagation of those signals; and the seeker tracks those signals. In each column, possible solutions are shown.

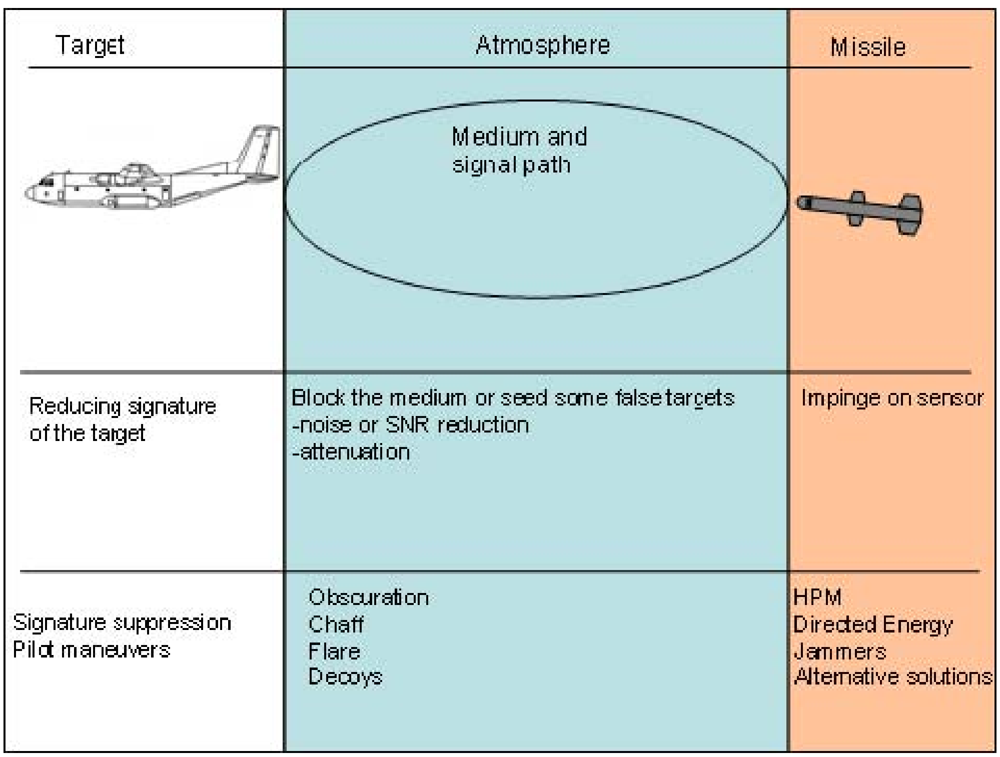

Figure 47. Countering threats.

For three basic threats (RF, IR/UV, Laser) basic concepts are highlighted below.

- Against RF
  - Target: The signal should be absorbed or reflected to other directions other than threat receiver.
  - Atmosphere: Deception. There should be some other materials, namely chaff, decoys, or towed decoys, to reflect the radar signals back so that the missile radar or radar track can establish on the wrong, fake, target.
  - Missile: Jamming the missile seeker or ground radar for tracking errors, blinding the missile's antenna and electronic components, or destroying the electronic components of an RF missile by high-power microwave.
- Against Infrared/Ultraviolet
  - Target: Reducing or suppressing the target's signature or noise can be added.
  - Medium: Deploying decoys or flares.
  - Sensor: Jamming. Emitting high-power signals to a wide angle or narrow angle to the lenses or sensors of the missile.
- Against Laser
  - Target:
  - Medium: Reflecting the laser in a different path by means of decoys in the laser's path.
  - Sensor: Jamming. High-power signals may be directed into detector elements of laser receiver and seeker electronics.

Basically, all countering systems use deceptive or destructive methods. The missile can proceed to the target unless there is no stronger IR or RF source, and no clutter in the field of view.

In Figure 48, different solutions are shown to give a general view for countering a SAM attack.

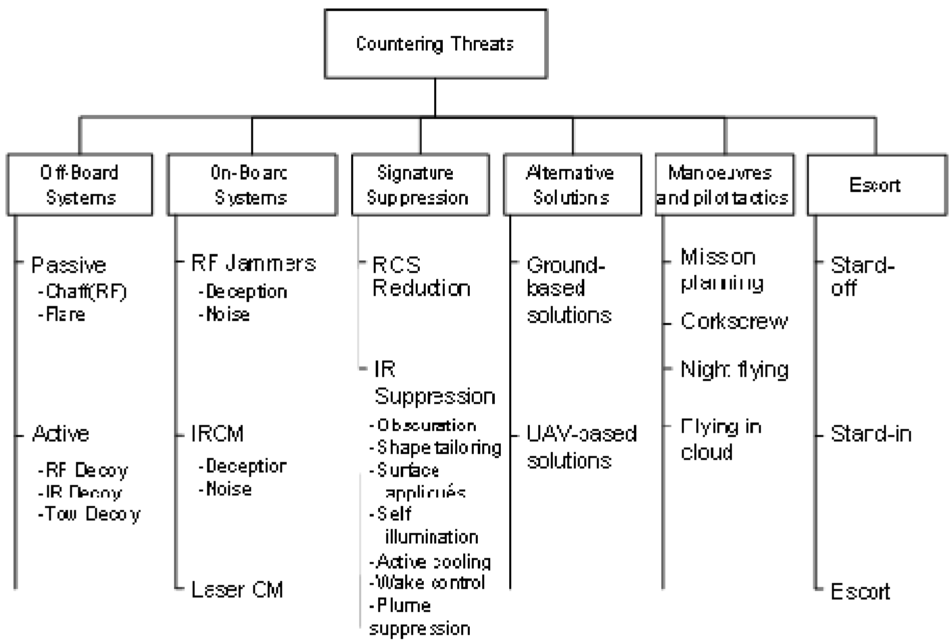

Figure 48. Countering threats.

A. OFF-BOARD COUNTERMEASURES (EXPENDABLES)

Expendables are countermeasures (CM) that are used to deceive the threat by deploying off-board things that are capable of reflecting signals, transmitting RF signals, or emitting an IR signature, according to the type of threat sensor. By imitating the target, they cause the missile to divert from its original target. They are relatively cheap and, like ammunition, they are limited onboard. Since there is a finite number available, when they are completely dispensed, the platform becomes unprotected. Most primitive expendables are of the free-fall type, which can be filtered out by velocity or Doppler effects. Before releasing the expendables, the important decision-making questions are, “When, how many, how often, which direction, and against what?” There are three kinds of off-board CM: free-fall, propelled, and towed decoy.

1. Passive Off-board CM

a. Chaff

Chaff is the oldest method of radar countermeasure. The chaff is made up of small strips that act like antennas, electromagnetic dipoles that re-radiate the pulses of the radar passively. By using the least amount of material and a relatively high RCS, the dipoles are cut to the first resonance point. The gain depends on the angle.

Length = $\lambda_0 / 2$

Chaff forms a cloud of very small dipoles, which creates backscatter in which to conceal targets. In the past, the chaff was laid for creating corridors to conceal attacking aircraft. Nowadays, the main purpose of chaff is for self-protection to break the radar lock-on function of a fire-control anti-aircraft gun or missile system. It is employed in the “end of game” scenario. The size of the chaff cloud should be several times larger than the radar return of the target aircraft.

When entering a battlespace, there are different threats employing different frequencies. When a wide range of radar frequencies must be countered, the chaff is cut to a pattern of different lengths to optimally cover the necessary frequency ranges. The chaff cloud causes the radar to switch its tracking lock onto the cloud.

In Figure 49, the resonance for a single dipole and three dipoles are shown. A single dipole is effective in 3 GHz and its resonant frequencies: 6, 9, 12, 15, etc., GHz. When there are three different lengths of dipole, their resonance frequencies cover the other frequencies by adding to each other.

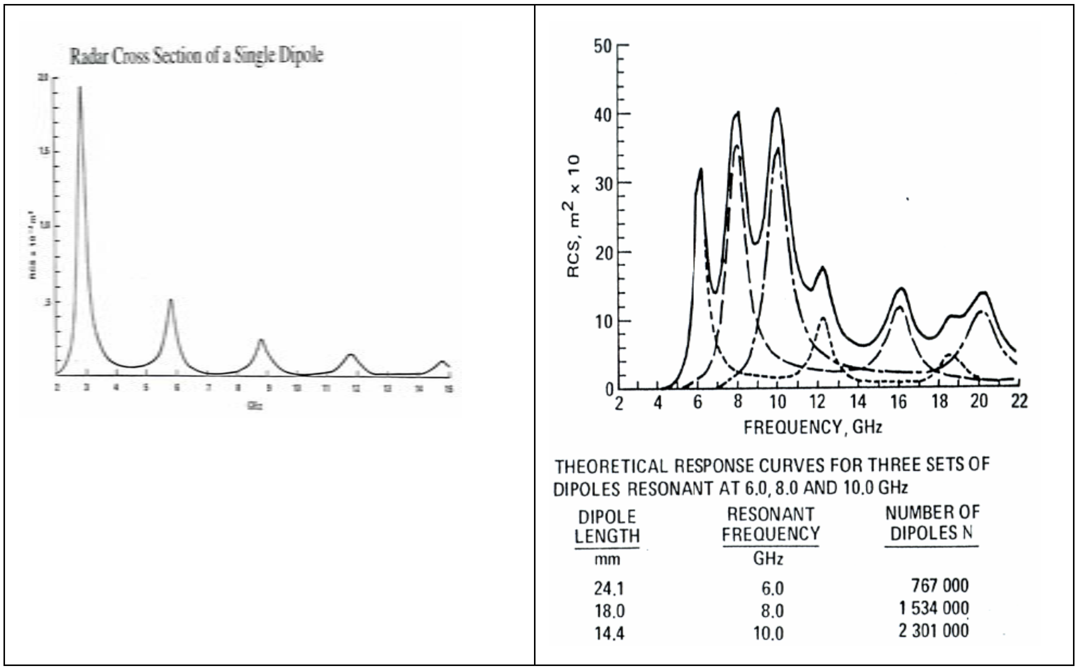

Figure 49. Backscatter from a single dipole and three dipoles.[51]

When chaff is dispensed, its velocity decreases very rapidly due to drag. The chaff cloud, which consists of millions of dipoles, grows rapidly. The distribution of the chaff cloud is affected by the launching aircraft, dispenser design, and the position of the dispenser on the aircraft. The width difference, which causes weight differences among the dipoles, also affects the chaff cloud's growth since the heavier dipoles fall faster than the lighter ones. The fall rate of the chaff varies from 0.1 to 1.0 meters/second depending on weather conditions.

The maximum cloud size is gained when it is as large as mathematically possible. N is the number of dipoles in a chaff cloud. Λ0 is the wavelength of the threat radar. The theoretical RCS of a randomly oriented half-wave dipole is:

$$RCS_{dipole} = 0.155\lambda_0^2$$

$$RCS_{\max} = N \cdot RCS_{dipole} = N \cdot 0.155\lambda_0^2$$

51 Philip Pace, "Introduction to Joint Electronic Warfare Class Notes," 2006.

Figure 50. Chaff.[52]

To protect a large aircraft, the cloud must be at least $300m^2$, and the threat could be X-band radar, which has a wavelength of 0.03m. Therefore, there must be at least 2,150,537 dipoles.

Since each dipole is like a piece of hair, it takes several hundred million of them to build an effective chaff cloud. As the chaff cloud expands, its density decreases and the separation between the dipoles becomes larger.

For an optimized usage of chaff, the important factors are:

- Chaff type (aluminum-coated glass chaff are more commonly used)
- Chaff length (chaff dipole cuts, resonance of half the wavelength). It should cover the threat radar's wavelength.

52 Wikipedia contributors, "Chaff," http://en.wikipedia.org/wiki/Chaff (accessed 20 March 2008).

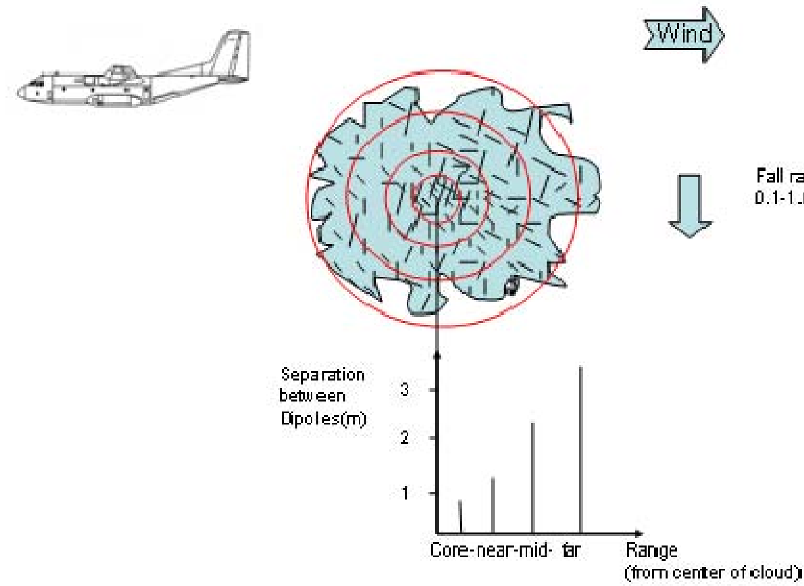

Figure 51. Chaff Cloud.

- Number of different chaff cuts in a cloud to counter multiple threats. The threat radar's wavelength may be unknown beforehand; therefore, a number of different chaff cuts must be in the cloud to provide full coverage.
- Burst intervals (in modern dispensing systems, 30–50 milliseconds) and an adequate ejection sequence
- Dispersion duration to create shielding (sometimes referred to as blooming time, it is the time that it takes for the chaff cloud to reach its maximum backscattering area).
- Location of the dispenser. For distribution purposes, they can be mounted on two different sides of the wings, enabling the airflow and engine exhaust to disperse them more efficiently.
- The type of dispenser.
- The type, size, and speed of the aircraft.
- The type of threat radar.
- The operating wavelength of the threat radar.
- Weather (wind, rain, air turbulence, etc.)

- Birdnesting (poor chaff dispersal caused by adhesion between dipoles and entanglement due to lack of stiffness). A low incidence of birdnesting provides a more effective RCS and better distribution of dipoles.
- Jackstrawing (poor chaff dispersal caused by the tangling of stiff dipoles even where no physical adhesion occurs).
- Shielding (occurs when the dipole density prevents every dipole from receiving the full amount of radar energy).
- Effective lasting time (lightweight makes the fall rate decrease, which enables a greater effective lasting time.

An RWR gives a warning to initiate the launching of chaff at the right time. Then, before launching the chaff, the pilot should execute a maneuver to present a very low Doppler return to the threat radar. The chaff is launched and then the aircraft resume its course.

For a typical short-range air defense missile with an engagement range of 7 km with an aircraft:

Beamwidth=2° in azimuth and elevation

Pulsewidth=range gate= 400 ns

$$Beamwidth(m) = \tan(beamwidth^{\circ}) \cdot Range = 244.4m$$

$$Pulsewidth = \frac{c \cdot \tau}{2} = 60m$$

For an aircraft traveling at a speed of 250 knots (129m/s), it takes 1.95 seconds to cross the radar resolution cell (251 meters) diagonally.

One cloud of chaff is not enough to broaden and cover the radar resolution cell. Therefore, a few chaff bursts must be dispersed in intervals of 30–50 ms.

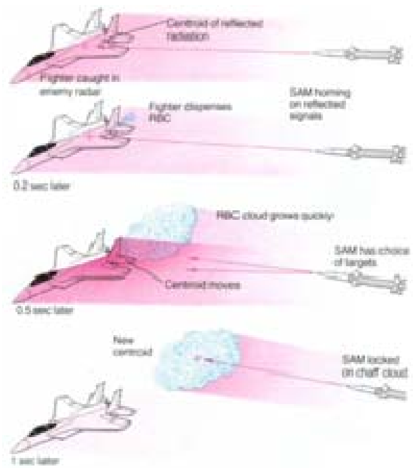

Figure 52. Self-protection.[53]

Some radars ignore a chaff cloud because its velocity decreases rapidly. To defeat this problem, aircraft should dispense a series of chaff clouds, rapidly and in a sequence according to enemy radars' capabilities. It produces the illusion that the cloud is traveling at nearly the same speed as the aircraft. The rapidly dispensed chaff clouds will "walk" the radar behind and off the aircraft as in Figure 52. Chaff backscatter must become larger rapidly when in the same radar resolution cell with the aircraft in order to break lock-on.

[53] Aerospaceweb, "Missile Countermeasures," http://www.aerospaceweb.org/question/electronics/q0191.shtml (accessed 20 March 2008).

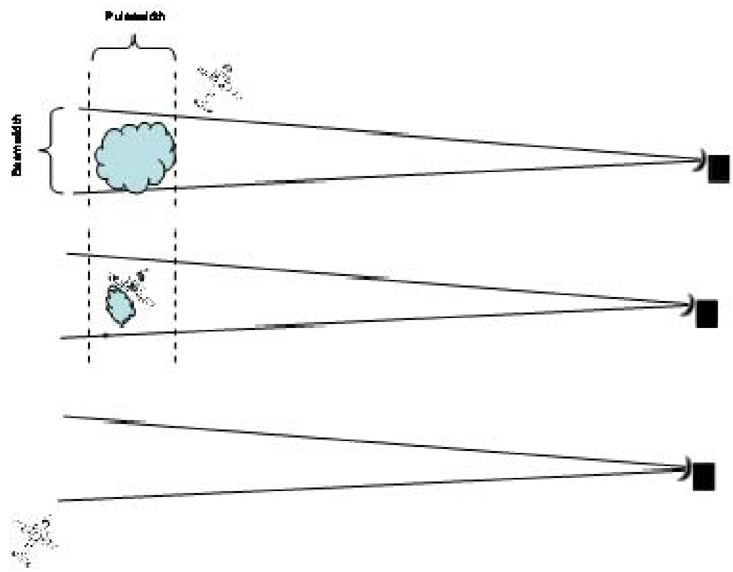

Figure 53. Chaff for self-protection.

Chaff can be used to form a corridor to hide the aircraft for different missions. In Figure 54, an aircraft seeds the corridor and leaves the area, then the formation of aircraft can go forward without being seen by radar.

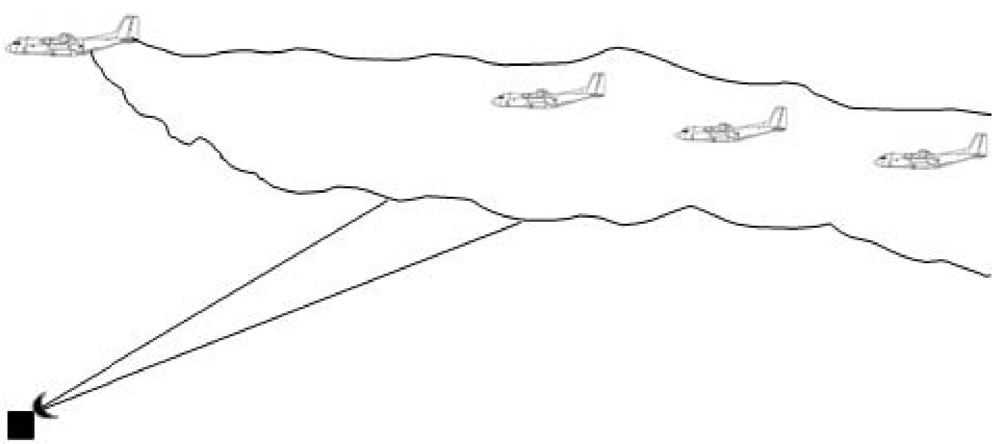

Figure 54. Chaff corridor.

b. Flares

IR flares are used against IR-tracking threats. Flares are effective against early types of IR missiles, which utilize passive guidance and employ hot-spot trackers. Spin scan and conscan seekers track more intense sources. Flares emit a high-intensity radiant, which lures the missile only for a few seconds. Therefore, it is important to dispense the flare at an appropriate time and direction to be effective. Missile approach warning systems warn the pilot to take evasive action against IR missiles. There are three ways to use flares:

- Seduction: To disengage an actively tracking target.
- Distraction: Used against threats before engagement or tracking.
- Dilution: Target and decoy at the same time.

To counter the missile seeker, a flare must rapidly produce two to five times the energy in the particular band that an aircraft produces.

The flare and decoys have some properties that distinguish and discriminates one from another.[54] These properties are used in improving missiles so that they will reject a flare by comparing the IR flare and the target signature:

- Rapid rise time. While the flare or decoy is in the field of view of the seeker, in a very short time, it should produce an intensity sufficient to be tracked by the missile.
- Sufficient energy output to ensure that the missile does not reacquire the target.
- Peak intensity should be higher than that of the target to lure the missile away.
- Spectral characteristics, which depend upon the burning characteristics of the fuel.
- Sufficient function (or burn) time to allow the target to maneuver out of the field of view before the missile can reacquire the target.
- Sufficient ejection velocity to assure separation from the aircraft. When the missile hits the decoy, its impact should not affect the aircraft.

[54] Accetta and Shumaker, 293.

* Aerodynamic characteristics. It is easier to reject decoys in free-fall.
* Size. The flare should be big enough to counter imaging seekers.
* Dispensing sequence and intervals. For optimal effects.

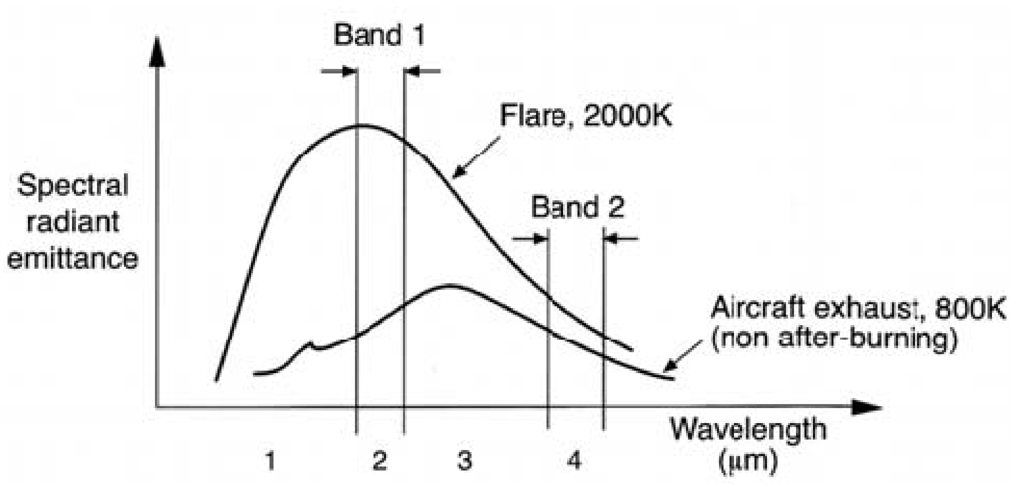

Figure 55. Flare and aircraft spectral radiant emittance.[55]

Newer generation missiles employ imaging-type seekers that can discriminate the flare and reject it.

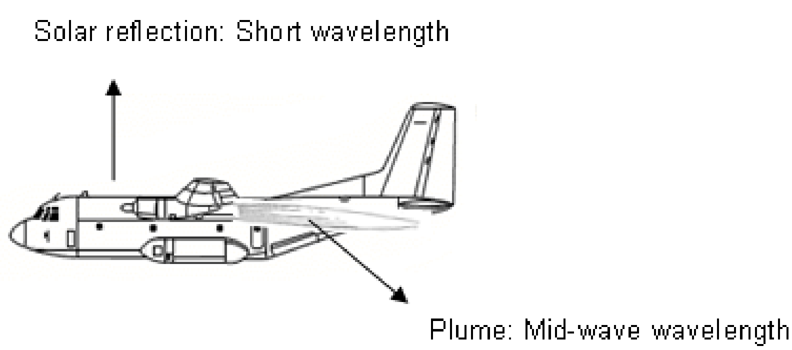

Figure 56. Signatures from a turboprop aircraft.

55 Browne and Thurbon, 275.

Multi-spectral or multi-color sensors are another effective method of rejecting flares. A flare must burn at a higher temperature to produce more energy and its spectral radiant emittance is different. In other words, its emissivity will always differ from the actual target. Therefore, a missile's seeker can rapidly discriminate among energy levels, temperature differences, shapes, and sizes and can just ignore those signatures for a period, generally 20 seconds. A sudden velocity decrease is another way to reject the flare.

MANPADs have a short range and a short ceiling. Aircraft are usually at low altitudes when vulnerable to them. From the environmental approach, the use of a flare over a city or civilian locations presents a great chance of fire and related hazards on the ground since they are at low altitudes. Furthermore, it gives a great opportunity for the operator of the MANPAD to hide in such a place.

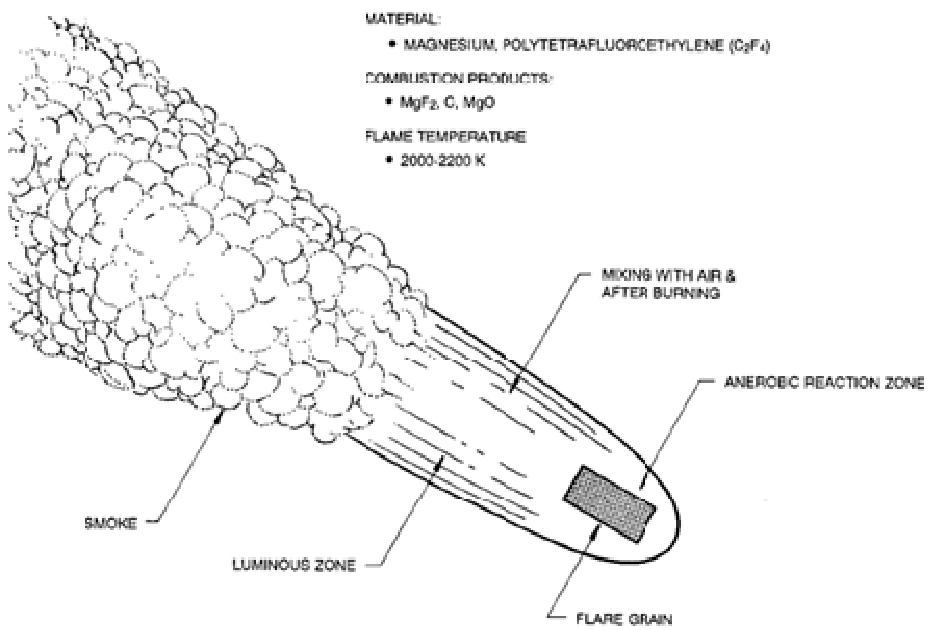

Figure 57. Flare.[56]

56 Cooper.

In Figure 57, the cloud of smoke is a discrimination technique for missile detection. Therefore, the plume must be made smaller by increasing the size of the flare or increasing the capability of the chemical.

A flare's plume is produced by pyrotechnic reaction. Pyrotechnics provide sufficient peak energy intensity, a long shelf life, and are fairly cheap. Atomized magnesium powder and polytetrafluoroethylene (PTFE) resin are the most commonly used pyrotechnic compositions.[57]

Imaging or quasi-imaging seekers can discriminate flares. New flare rejection techniques have been developed so there is a certain need for advanced flares.

Another approach is to release these pyrophoric flares with a tactical air-launched decoy (TALD), seeding flares before aircraft enters a corridor. Some flare types are:

Standard Flare: MJU-7, MJU-10

Spectral Flare: Tracor, Thiokol (2), Kilgore

Aerodynamic Flare: Kilgore (2), NSWC Crane

Special Flare: Alloy-SHS, Alloy-LTE

2. Active Off-board CM

a. Kinematic Special Material Decoy (IR Decoy)

Since free-fall flares can be discriminated by velocity deceleration techniques, powered decoys, which can fly for a time, have been developed. Loralei (Lockheed Martin) makes use of this technique.

57 Accetta and Shumaker, 299.

b. RF Decoy Systems

Decoys receive a signal, modify it, and then retransmit the amplified signal. Therefore, they are different from chaff, which only reflect the signal. Decoys were developed when the home-on-jam types of threats increased. They are particularly effective against missiles employing monopulse and Doppler radars, which are difficult to counter by other means.

There are basically three types of decoys: non-propelled, propelled and towed.

Active decoys are produced by gallium arsenide (GaAs) monolithic microwave-integrated circuit technology. The battery time and shelf life are big problems. Therefore, to extend their effectiveness, they must be launched when the missile is approaching and at the right range. If that information is not known, then, at proper intervals, many decoys should be launched, starting when a CW emission illuminates the aircraft.

Repeater towed decoys easily generate the CW jamming signal with the associated necessary Doppler frequency.

Fiber-optic towed decoys are more advanced.

POET	Lockheed sanders
Description:	The first modern, active, expendable decoy. (Primed oscillator expendable transmitter)
GEN-X	Texas Instruments
Description:	Multi-threat, wide-frequency coverage, broad antenna pattern, modulation programmable, no aircraft mods, self-contained unit, thermal battery, operational life, 5-year shelf life.
Features	Digital RF memory(DRFM)
TALD	ADM-141A
	Glider decoy
MALD	Miniature Air Launched Decoy

Table 19. Some countermeasure examples.

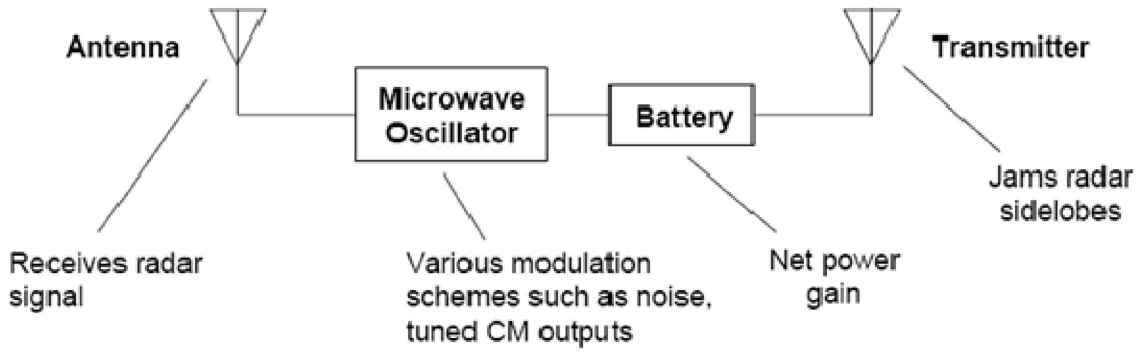

Figure 58. Typical decoy block diagram.

c. RF Towed Decoy

Towed decoys are effective against monopulse seekers (simultaneous lobing tracking), which have the advantages of getting an angle error estimate from a single pulse return, a short integration time, and are resistant to noise jamming. The cable should be longer than the missile's lethal radius.

A decoy towed by an aircraft has some benefits. It travels at the same speed as the aircraft, it is powered from a different source, and it travels at a distance from the aircraft. Towed decoys produce signals much larger than the towing aircraft. Towed decoys are very effective against monopulse tracking radars and missiles, which reject angle deception.

Noise jammers are countered by monopulse tracking radars. The monopulse tracking gives a strong home-on-jam capability. Moreover, onboard jamming techniques are very difficult to implement. Today, most ground defense systems have powerful Doppler filters. To deceive the threat, one must first be able to bypass the filter. A towed decoy transmits the jamming signal.

Since towed decoys are small, if the missile approaching from behind misses the towed decoy and does not explode by proximity fuze, it will become a problem for the aircraft. Therefore, the pilot should know the missile's

angle of arrival and maneuver so as not to give much jamming-to-signal ratio or introduce more RCS by banking. Whenever the towed decoy is hit, then a second one must be ready for the other possible threats.[58]

AN/ALE-50	Raytheon
Description:	Advanced Airborne Expendable Decoy (AAED) is a towed decoy that acts as a preferential target luring enemy radar-controlled missiles away by providing a much larger radarcross section than the aircraft.
	ALE-50 has no fiber-optics and generates its own electronic response to enemy threats.
AN/ALE-55	BAE Systems
Description:	Fiber Optic Towed Decoy (FOTD)
Features	The AN/ALE-55 fiber-optic towed decoy and the AN/ALQ-214 radio frequency countermeasures (RFCM) are used together. The onboard portion of the RFCM system is designed to receive radar signals from potential threat emitters via antennas on the forward and aft sections of the aircraft and to generate an electronic countermeasures response to the threat. Jamming may use either onboard transmitting capabilities or the off-board transmitting capabilities of a towed decoy. For the off-board response, an effective jamming signal is generated by onboard RFCM equipment and provided to a decoy towed behind the aircraft for amplification and transmission. To reach the decoy, the signal is converted to light and transmitted down a fiber-optic link to the decoy. In the decoy, the light signal is converted back to RF, amplified, and transmitted using antennas integral to the decoy.

Table 20. Some examples of towed decoys.

3. Ejection Methods of Expendables (Countermeasure Dispensing Systems)

Dispensers are installed outboard to make use of good air flow. Today's dispensers can have a combination of IR, RF expendables and decoys. Smart dispensers can run multiple dispense programs. Dispenser systems have a control unit, a sequencer, a programmer and a dispenser. The programmer controls the rate and type of expendables. Deployment methods can be mechanical, pyro, rocket, or mortar.

58 Neri, 471.

AN/ALE-47	Symetrics
Features	The AN/ALE-47 is capable of carrying a mix of expendable countermeasures including expendable jammers.
	
AN/ALE-39	ALE-39 burst intervals are hardware limited -125 milliseconds for chaff -2 seconds for flares, 1 second intervals for jammers[59]

Table 21. Some examples of CM dispensing systems.

B. ONBOARD COUNTERMEASURES

There are several types of onboard countermeasures designed to protect the platform. The number of missiles to be engaged is one important evaluation of these systems.

1. RF Jammers (Onboard RFCM)

In today's battlespace, multiple threat attacks may occur simultaneously. Prioritizing those threats is an important task. Multiple repeater and multiple transponder RF generators can accomplish simultaneous countering. The

59 "Advanced Technology Expendables and Dispenser Systems Program Review," 6th, Monterey, CA, and (U.S.) Naval Surface Warfare Center, Crane Division, 1996.

jammer must cover the full radar band (0.5 GHz to 18 GHz). Large aircraft have enough power and space for big systems but as the aircraft size increases, the RCS increases. This phenomenon requires more jamming power.

$$J / S = ERP_J - ERP_S + 71 + 20Log(d) - 10Log(RCS)$$

Onboard radar jammers have some inadequacies:

- They cannot provide 360° angular coverage. They can have ± 60 degree angular fore-and-aft protection.
- Frequency range cannot cover the whole band.
- Processor is not capable of handling a number of pulsed and CW simultaneously.

RWR must provide the jammer with:

- The signature of threat
- The precise threat location
- Priority

The burn-through range is the range at which the target's jamming loses its effect on the radar and can be detected. It is the range at which there is no longer an adequate jamming-to-signal (J/S) ratio.

$$R_{BT} = \left(\frac{JSR_P \cdot ERP_r \cdot B_j \cdot \sigma_T}{ERP_j \cdot B_r \cdot 4\pi} \right)^{\frac{1}{2}}$$

Active jamming includes disruptive or deceptive jamming.

AN/ALQ-162(V)	Northrop Grumman
	AN/ALQ-162(V) (also known as Shadowbox) is a single Weapon-Replaceable Assembly (WRA) that incorporates transmitter, receiver/processor, user data memory and an antenna module. It is a continuous wave, chopped repeater jammer that can operate autonomously or be interfaced with other onboard electronic warfare equipments. The system provides self-protection against radar threats by continuously scanning the threat signal environment, identifying emitters and then generating specific countermeasures against prioritized threats. The equipment's user data memory module is a single printed circuit assembly (with a programmable read-only memory) and provides a reprogrammable data bank for system control parameters, threat tables, threat priorities and modulation techniques. The antennas provide nominal coverage of ±60° in azimuth and ±30° in elevation.
AN/ALQ-214	Lockheed Martin
Description:	Integrated Defensive Electronic Countermeasures(IDECM) RFCM
Features	The major hardware component to be developed by the IDECM program is the IDECM radio frequency countermeasures (RFCM) system and the ALE-55 Fiber Optic Towed Decoy (FOTD), which is trailed behind the aircraft to optimize RFCM techniques against threat missiles and tracking/targeting systems. The RFCM consists of an on-board receiver/processor/techniques generator that stimulates the FOTD via fiber optic cable or on-board transmitters for transmission of the countermeasure technique.

Table 22. Some examples of jammers.

Onboard jammers use either noise or deception jamming.

a. Noise Jammers (Denial Jamming, Obscuration Jamming)

Radars can detect a signal that is above the sensitivity level of its receiver, which is defined as the signal-to-noise ratio. If the noise is more than the signal, then the signal cannot be detected. A jammer must generate noise similar to the threat radar's thermal noise. Jammer characteristics:[60]

- Spatial coverage
- Frequency coverage
- Receiver sensitivity
- Dynamic range
- Tuning precision
- Noise bandwidth

[60] Neri, 381.

- Noise quality
- ERP
- Polarization

Noise jammers are an early type of jammer. They obscure the radar screen. Direct noise amplification, which filters the original noise and directly amplifies it, is not popular today.

White noise has a Gaussian distribution, and its spectrum is uniform. Some noise generating methods:

- Traveling wave tube (TWT) type
- Types of Noise:
- CW
- Swept CW
- Spot noise
- Barrage noise
- Gated noise
- Smart (coherent) noise

A jammer transmits noise at the same frequency or frequencies as the adversary radar. If that is in a particular band, then it is called spot jamming. If it transmits in a range of frequencies, then it is called barrage or broadband jamming. Bandwidth ratio describes the type of noise jamming.

$$\frac{BW_j}{BW_r} >> 5$$ Barrage jamming

$$\frac{BW_j}{BW_r} > 1-5$$ Spot jamming

Noise jamming is more effective against the main lobe.

Noise jamming is not effective against monopulse radars. However, a threat to jamming is home-on-jam (HOJ) missiles. Two aircraft can defeat HOJ by alternatively jamming (blinking), causing the missile to be confused as to where to go.

b. Deception Jammers

Deception jammers provide the radar with erroneous information, i.e., false targets. They break tracking lock by pulling the radar off in range or angle.

Deception jamming (repeater jamming) can be used against search and tracking radars. Deception jamming is more effective than noise jamming because modern radars implement coherent techniques.

Deception jamming causes tracking radars to break angular tracks. Since tracking radars have narrow-angle beams, they lose the target, range and velocity information. It generally takes 10 or more seconds to reacquire. Different kinds of deceptive jamming are:[61]

- Range gate pull-off
- Inbound range gate pull-off
- Cover pulses
- Inverse gain
- Automatic gain control (AGC) jamming
- Formation jamming
- Blinking
- Cross-polarization
- Cross-eye

[61] Adamy, 2003, 50.

Coverage +/- 50az +/- 20 elevations

AN/ALQ-122	(Motorola)
Description:	Multiple false target generator

Table 23. An example of a deception jammer.

Digital radio frequency memory (DRFM) capability is needed against pulse Doppler radars. It receives the RF signals of a hostile radar and delays them by modulating and manipulating those signals it transmits.

RF jammers on large aircraft are feasible since they can generate enough power. But they can be placed on only bombers or other high-value platforms.

2. Active IRCM (Onboard IRCM)

Active infrared countermeasures basically add modulated IR energy to the aircraft's signature to jam the IR-guided missile. IR energy sources come to the detector and the signal processor determines the position of the target. The seeker tracks the highest radiant intensity.

IR jamming causes an optical breaklock (loss of target tracking). An early breaklock is ideal but, due to long-distance attenuation of IR, it cannot be feasible. The important criterion is to gain a breaklock beyond the lethal range of the missile warhead.

Active infrared countermeasures manipulate the infrared signature of an aircraft by adding modulated infrared energy to the infrared signature of an aircraft to deceive missiles. This procedure can cause to the seeker to lose the target completely and, in turn, affects the guidance function of the missile. In Figure 59, an IRCM jammer, is shown on a Boeing 747.

Figure 59. IRCM on Boeing 747.[62]

Arc lamps or graphite elements are used to transmit IR pulses received from the IR seeker's reticle with the aircraft's signature. When both of them come together, they give wrong information to the missile. Large aircraft have large signatures. To defeat the missile, one needs more power to overcome this phenomenon.

To saturate the signal processing in the missile, large jammer signals must be introduced to the missile's seeker.

Atmospheric attenuation, shielding, and other factors reduce the effective range for an IR missile to acquire the target. While IRCM can protect a C-130-size aircraft, they cannot protect larger aircraft, such as C-17, C-5, and other similar aircraft, due to lack of jamming-to-signal ratio.

Older versions of IRCM systems use wide-angle heat lamps, roughly similar to isotropic RF antennas, but these systems do not radiate enough energy

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62 Global Security, "AN/ALQ-204 Matador Infrared Countermeasure (IRCM)," http://www.globalsecurity.org/military/systems/aircraft/systems/an-alq-204.htm (accessed 20 March 2008).

since they distribute the energy in a wide-angle direction and also alert the enemy of the presence of the aircraft. Thus, directed IRCM systems were developed.

IR-tracking sensors are more susceptible to CM during the acquisition phase.

a. Directional Infrared Countermeasures (DIRCM)

When the threat was only in the 1.9–2.9 μm band, the aircraft were threatened by only the hot parts in the aft portion; therefore, IRCM systems used a reflector to send the jamming radiation to the aft side of the aircraft. At that time, no missile launch warning was required because the radiation pattern was large. Therefore, they were not as complicated as today's systems.

After missiles began to use the 3.0–5.0 μm band and improved scanning systems (conscan and rosette), arc lamps and carbon rods became insufficient to divert the missile. IRCM radiates energy in all directions, like an isotropic antenna. Directional IRCM systems concentrate the energy onto the missile. Since it is directional, it needs less power because the power is radiated to a solid angle. However, in order to point directly on that threat in space, it is necessary to have information from the missile system that gives the presence and arrival angle of missile.

A seeker can be illuminated by a large amount of radiation, causing damage to the detector, reticle, or filter, ending the threat because it is unable to track. A narrow-beam laser can be directed at the seeker for enough time to cause that damage. A reticle is easily damaged with less power, since it is a thin film. Dome damage requires an out-of-band high-power laser and this energy can be supplied by ground-based laser sources.

DIRCM integrates missile warning and the IR jammer to counter first- and second-generation IR missile threats. DIRCM detects the missile launch with AAR-44 and/or AAR-54, then hands off MWS acquisition to a fine-track

sensor via DIRCM processor, acquires the target with the IR fine-track system, and defeats it. DIRCM are ineffective against missiles that use laser beam-riding guidance.

AN/AAQ 24	(Northrop Grumman) Nemesis LAIRCM
Features	Next-generation integrated countermeasure system. AN/AAR-54(V) which is a 256x256 staring array fine tracking subsystem detects missile's plume and provides bearing data to the AN/AAQ24(V). The turret of the DIRCM then swerves around and fires a laser beam at the seeker head of the missile.
AN/ALQ204	BAE systems
Features	AN/ALQ204(Matador) consists of multiple transmitters each transmitter contains 4-12 kW source that emit pulsed infrared radiation.

Table 24. Some examples of DIRCM systems.

b. LAIRCM Second Phase

Today's systems use open-loop IRCM lasers. They track via missile signature, generate a generic jam code by sweeping multiple threat frequencies, and confuse missiles with random false targets or IR energy. By degrading the guidance of the missile, it makes the missile wobble in flight but not necessarily break lock. The missile can then reacquire the target if the jam head moves to another missile. According to the predicted time of flight of the missile it jams, it then breaks off to switch to next threat after a few seconds.

Pros: Continual protection

Cons: Needs auxiliary power; size and weight

A closed-loop IRCM laser tracks the missile whether active or passive. It has a higher power narrow-beam laser. It classifies incoming missiles, identifies their type, and predicts their time to impact. Then the highest priority missile is jammed with a custom jam code in a sequence that would cause the

missile to break lock and move sharply away from the target aircraft, allowing the engagement of another target after only 3–4 seconds. Therefore, it has a quick optical breaklock.

Pros: Real-time classification of threats and positive tracking of missiles allow narrow-beam and higher S/J ratio. Optimal jamming enables the breaklock at a long distance.[63]

None of the countermeasures is protective against all threats:

- Noise jammers swamp the target signal with excessive signal.
- Deception jammers cause the tracker to give erroneous data.
- Destructive jammers destroy the sensor of the seeker by transmitting energy.

3. Jamming and Chaff (JAFF) (Illuminated Chaff-CHILL)

An onboard jammer illuminates the off-board dispensed chaff with either deception or noise signal. Therefore, the chaff can reflect two Doppler effects: one from the tracking radar and the other coming from the onboard jammer. For implementing this technique, antennas can be steerable according to information of the angle of arrival. This technique is used against coherent radars, which reject static targets.[64]

4. Laser CM

Laser CM are similar to rangefinders, having short duration and low repetition rates but with a higher intensity. The laser has a plasma spark effect in the seeker head close to the detectors. The energy from the plasma effect causes jamming and blinding effects. It may also cause some pits and scratches in optics, creates some debris, and negatively affects the electronics near the seeker.

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63 "Advanced Technology Expendables and Dispenser Systems Program Review," 6th, Monterey, CA, and (U.S.) Naval Surface Warfare Center, Crane Division, 1996.

64 Neri, 452.

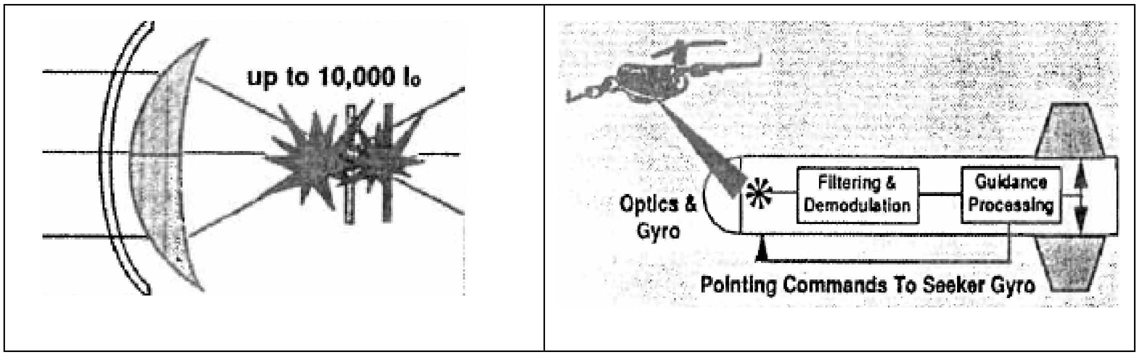


Figure 60. Laser plasma.

Lasers can cause thermal degradation/damage to detectors from a long (200 nsec) pulse effect. Plasma effects come from short (0.1–50 nsec) pulses. Optimum effects may require lasers at multiple, tunable, or broadband wavelengths.[65]

5. Directed-Energy High-Power Microwaves (HPMs)

Directed energy, as in radar and laser, has the advantage of the speed of light. Even for a missile, it takes an average of 7 seconds to hit the target but here, for a 6000 m target:

$$t = \frac{d}{c} = \frac{6000}{3 \cdot 10^8} = 50 m \sec$$

High-power microwave energy disrupts or destroys missile circuits and drives missile away from aircraft. It is effective against IR, EO and RF missiles. Ultra-wide band sources eliminate the need for specific knowledge of threat missiles. Narrow-band effects are well documented. The effectiveness of HPM increases as the missile become more sophisticated because the increasing amount of electronics in the missile makes it more vulnerable to HPM.

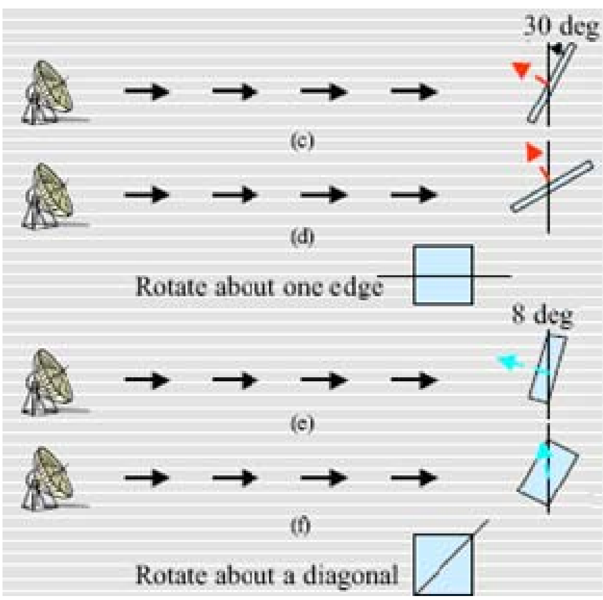
65 “Advanced Technology Expendables and Dispenser Systems Program Review,” 6th, Monterey, CA, and (U.S.) Naval Surface Warfare Center, Crane Division, 1996.

C. AIR VEHICLE SIGNATURE SUPPRESSION (SIGNATURE REDUCTION)

1. RCS Reduction

For reducing the RCS, vertical surface designs incorporate canting and swept leading edges. They should be designed to reflect the radar signals anywhere but back to the radar receiver.

Figure 61 shows how this theory works. When we rotate the edge of the aircraft, the return decreases.



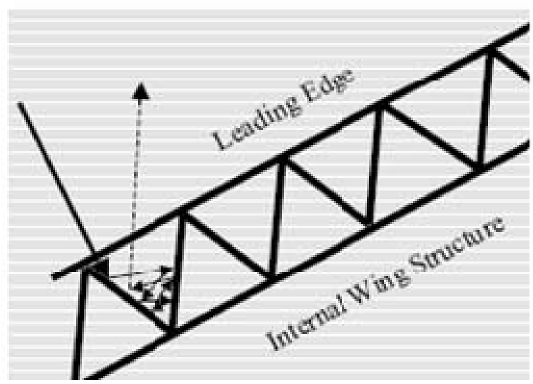


Figure 61. RCS reduction.[66]

The engine inlet, engine, and exhaust are hidden above the wing. All other components around the aircraft are very important details.

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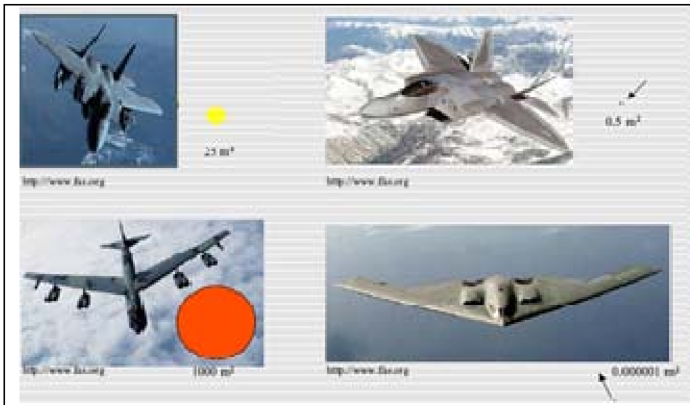
[66] David Hall, David Andrews, Sangeon Chun, "Stealth," http://209.85.173.104/search?q=cache:ag9apasC05IJ:www.aoe.vt.edu/~mason/Mason_f/StealthS03.pdf+stealth+david+hall&hl=en&ct=clnk&cd=1&gl=us (accessed 20 March 2008).

Radar absorbent materials, such as dielectric and magnetic, can be used to absorb the radar energy.

To reduce reflections from the internal structure of the wing, leading edge construction should have a triangular shape.

In Figure 62, the importance of RCS reduction is shown by presenting different kinds of aircrafts and their RCS.



Aircraft	RCS (m^2)
Bombers	
B-52	1000
B-1A	100
B-1B	10
B-2	0.000001
Fighters	
F-4	100
F-15	25
F-22	0.5
F-117A	0.1
Cruise Missiles	
ALCM	0.25
ACM	0.001

Figure 62. Typical RCS values.[67]

2. IR Signature Reduction

Aircraft signature suppression devices shorten the acquisition range, enhance the performance of countermeasures, and reduce missile effectiveness from some aspects of attack. The concerns with the present suppressor systems are reliability, maintainability, loss of performance, cost, and interchangeability among aircraft types and engines.

Important signature suppression methods are as follows.[68]

67 Hall, Andrews, and Chun, 6.

68 Accetta and Shumaker, 189.

a. Shape Tailoring

Shape tailoring is directly concerned with RCS reduction (RCSR). In both RF and IR, the main concern is to reduce and eliminate reflections toward the seeker and receiver. RF threat sources usually have the transmitter and the receiver at the same location, i.e., monostatic. However, electro-optical sources are usually bistatic. Therefore, passive bistatic sources constrain the shape options.

b. Surface Appliqués

Coating modifies the reflective, self-emission, and directional properties of the surface characteristics, and they give different results in the visible, IR, and RF spectral regions.

c. Plume Suppression

Engine size reduction requires tradeoffs among speed, payload, airframe, and plume suppression requirements.

Cycle tailoring involves basic cycle configuration. Engine types are turbojet, turbofan, and turboprop. Due to needs in the aircraft missions, the cycle cannot be changed but they can be adapted for low observables. Higher bypass ratios supply greater air for exhaust cooling. In this case, the tradeoffs include cycle, mixer, nozzle, engine thrust fuel consumption, weight, and cost.

Placing the airframe's deck behind the exhaust obstructs the view of the nozzle and other hot parts as well as the plume. High-altitude aircraft use decks on the lower side of the engine; low-altitude aircraft use decks on their upper surfaces.

The other signature suppression methods are obscuration, self-illumination, active cooling, wake control, hot parts suppression, aircraft body signature suppression, and nozzle shaping.

3. Aural Signature Reduction

Baffles and louvers can be placed in the engine where airflow separation occurs Laminate-coating reduces emission of noise in the engine nozzle and is also effective for IR signature reduction. The surface of the aircraft should be smoothed and streamlined, enabling little friction when flying in the airflow. High-bypass turbofan engines suck in a larger quantity of air and do not accelerate as much. Placing the engine on top of the plane hides IR and aural signatures.

4. Visual Signature Reduction

Camouflage, coating materials, light-diffusing paint, and glint-reducing paints have some positive effects, especially at night. More efficient burning in the engines reduces smoke emissions. Fuel additives can reduce convection and engine exhaust contrails.

D. MANEUVERS AND PILOT TACTICS

Pilots always try to visualize the big picture in their mind: who is the enemy? They should always have a backup plan.

The best tactic is not to go where the threat is. However, if the mission dictates, then different tactics can be conducted by pilots according to altitude, speed, and environmental combinations restricted by aircraft maneuverability.

1. Changing Routes Often

Similar missions should not plan on using the same route. One F-117, which is a stealth aircraft, was lost in combat during the Kosovo War in 1999 when the Serbians moved the radar system just under the reported flight path. Therefore, mission planners should also know the capabilities and possible deficiencies of their systems.

2. Agile Maneuvers

Early SAMs employed IR sensors with very narrow fields of view. Therefore, when the aircraft turned sharply abeam of the threat (3–9 o'clock position) and dispersed chaff and flares, eventually the missile would lose sight of the target, breaking the lock.

3. Speed is Life

Another tactic is known as, "speed is life," in which the aircraft accelerates and makes evasive maneuvers so that the missile's limited fuel is expended before harming the aircraft.

However, large aircraft are not so agile; they usually cannot exceed 4 Gs of force and are unable to pass even Mach 1. Thus, these maneuvers are beyond the capabilities of most large aircraft.

4. Corkscrew

The most suitable tactic for large aircraft is the corkscrew. The corkscrew tactic involves climbing and descending in safe and protected places. After takeoff, the aircraft climbs in a spiraling or circling pattern and descends in a slow, tight circle, as if walking down a spiral staircase.

5. Flying Low

By flying low, the enemy has a minimum time for preparation, setup, and launch of the missile. If they do not have any other means of target detection, like integrated defense systems, which may give the information of target arrival, then flying low can be seen as a practical solution.

As an example, for an aircraft flying at an altitude of 15,000 feet and a range of 6–8 km, a MANPAD can be set up and hit its target in less than 19 seconds. For a MANPAD, visual detection and identification takes approximately 5 seconds. Activation and gyro-slaving for an old type of MANPAD takes 4

seconds. The missile flyout takes 7 seconds, so the pilot has 19 seconds to defeat the threat.[69] However, flying low is very risky because large aircraft have a large area vulnerable area to explosion when hit, namely, the fuel tanks along the wings.

If the mission is flown below 15,000 feet, the pilot flies very low and very fast. Therefore, the operator of the MANPAD may not have enough reaction time. However, after losing some aircraft in Desert Storm, it is understood that flying low is not a proper solution.

6. Fly in Cloud Tactics

Flying in a cloud, which is filled with droplets or ice crystals, can be a solution against EO/IR missiles because EO wavelengths are strongly attenuated. Small rain droplets cause more attenuation than the bigger raindrops. Attenuation and EO transmission through the rain are affected by the size of raindrops, rain rate, and path length in the air. However, this cannot be a practical solution and, as can be understood from Figure 63, it is useless against RF.

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[69] Mark Hewish and Juris Jannsen Lok, “Moderating MANPADs,” Jane’s International Defense Review, 1998, 53.

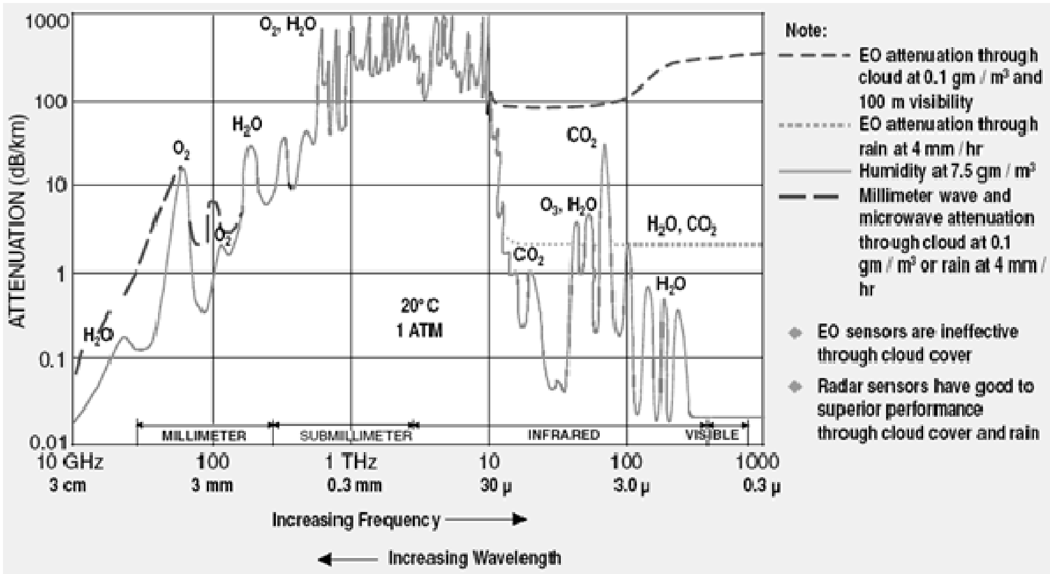

Figure 63. Seeker performance in adverse weather.[70]

7. Night Flying Tactics

For countering terrorist attacks, arriving and departing at night hides the aircraft's type and nationality. It disables visual tracking and acquisition by MANPADs. Lights-out approaches and takeoffs also contribute to the prevention of visual acquisition.

Therefore, mission planning, which includes weather, terrain data, intelligence about enemy defense systems, and coordination with all operating friendly forces, is important.

When an "air bridge" is established to a place, many troops and armored vehicles to support those troops are moved by large aircraft. If a SAM attack is executed against one of those aircraft, then the air bridge connection becomes damaged and the ground forces will have problems accomplishing their mission. Therefore, it affects the whole operation.

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[70] Eugene L. Fleeman, *Tactical Missile Design*, AIAA education series, 2nd ed. Reston, VA: American Institute of Aeronautics and Astronautics, 2006, 132.

Turning off radars, lights, and all IR- or RF-emitting systems also contributes to signature reduction.

If the aircraft has no detection system, then the expendables can be dispersed on a contingency basis, according to intelligence data. Since the flares are very bright and have smoky trails, they release a visual warning to missile operators.

Therefore, the aircrew of large aircraft is limited in what it can do against SAMs.

E. ALTERNATIVE SOLUTIONS

Helicopters and ground forces can be used for airport perimeter security as an active search for any attack elements. Unmanned aerial vehicles (UAVs) or balloons with cameras can passively track suspicious activities around the airport. The MANPAD threat and the cost of self-protection of each aircraft has urged aviation companies to find other solutions.

1. Ground-based Solutions

Protecting a large military aircraft is essential to operating in a dangerous environment. However, protecting each aircraft with self-defense systems is not feasible in commercial aviation since it is very expensive. For civilian airliners, the threat is concentrated on terrorist attacks carried out by MANPADs during the takeoff and landing phases of flight. Typical flight times range from 2 to 13 hours, and susceptibility to MANPADs occurs primarily during takeoff and landing, which is only 30 minutes of that time. Therefore, it is possible to protect the aircraft by means of ground-based facilities, which can be easier, less expensive, and less burdensome on the airlines in terms of the costs of extra weight, volume power, maintenance, modification, upgrade, and interference problems onboard.

Ground-based CM use the same principles and technology as airborne CM. However, these systems must cover a larger area. They have some advantages. Since they are in a fixed position, the background does not change so rapidly, which makes signal processing easier. Different warning systems fixed in different positions around the airport gives the opportunity of precise threat detection by triangulation; therefore, the false alarm rates decrease.

When the sensors hand off the threat information to target acquisition and tracking systems, the optical pointer tracker directs a laser beam onto the missile. The warning sensors and countering systems must be placed in a high position to be effective and cover all areas.

A typical approach and departure takes 10 nm from the end of each runway. Typical climb rates are 2000 feet per minute. An aircraft can climb 6000 feet by the time the aircraft reaches the boundaries of the threat zone. If the aircraft cannot climb to 15,000 feet upon reaching the boundaries of the protected area, then it should maneuver to climb at least 15,000 feet within this protection. The boundaries of the protected zone cannot be enlarged much due to the electromagnetic propagation capabilities of the countermeasures.

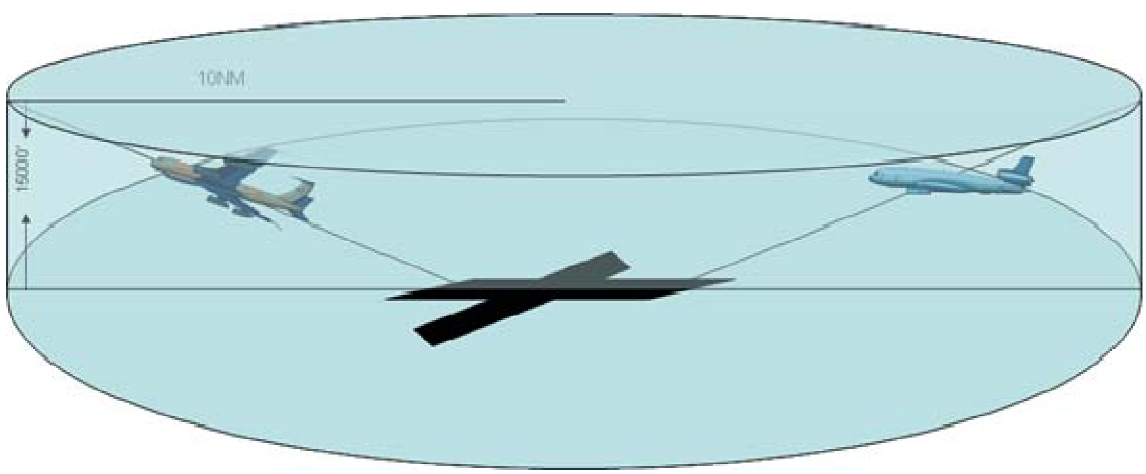

Figure 64. Protected zone.

Aircraft equipped with onboard CM must deal with the rapidly changing environment and complex background clutter problems caused by the speed and position of the aircraft. Ground-based systems are fixed or change their positions relatively slowly, so all background data can be saved and it is easier to find the changes caused, in this case, by a missile launch.

Ground-based countermeasures can employ as many sensors as they need. Multiple sensors enable triangulation not only to find the location of the missile accurately, but also to detect simultaneous missile attacks.

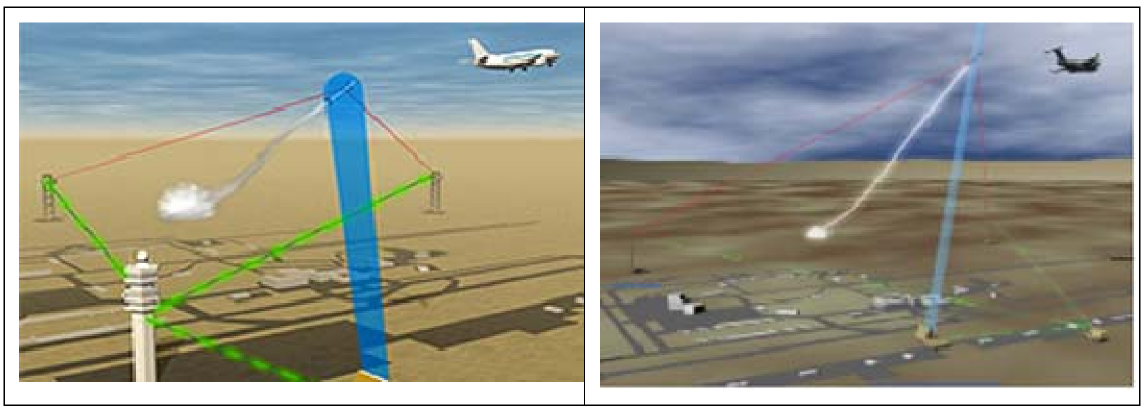

Figure 65. Vigilant Eagle system.[71]

Vigilant Eagle	Raytheon Company
Description:	When located at a commercial airport, Vigilant Eagle creates a dome of protection around the airport by illuminating the missile body with electromagnetic energy tailored to divert the missile. This system uses directed energy in the form of pulsed microwave to interfere with the guidance of SAM .
Features	Vigilant Eagle consists of three major components: a distributed missile detect and track subsystem (MDT), a command and control (C2) system and the Active Electronically Scanned Array (AESA), which consists of a billboard-size array of highly efficient antennas linked to solid-state amplifiers. The MDT is a fixed grid of passive infrared (IR) cameras that communicate with the C2. These IR cameras can be mounted to existing infrastructure to cover the required detection space. Each missile detection is confirmed by at least two sensors in an overlapping grid. This yields an extremely low false-alarm rate, demonstrated to be on the order of one or two events per year, thus minimizing impact on airport operations.

[71] Raytheon, “Vigilant Eagle,” http://www.raytheon.com/products/vigilanteagle/ (accessed 20 March 2008).

Vigilant Eagle	Raytheon Company
	The prototype high-power microwave (HPM) weapon, with its energy focused within 1 deg., sends an electrical pulse through the enemy missile's metal parts and into its computers and guidance system. For a split second, that spike is strong enough to damage electrical components and scramble computer memories so badly that the missile flies off course and ignores the aircraft it has targeted.
CMAPS	General Dynamics
Description	CMAPS is a ground-based system designed to protect airplanes from MANPADS during take-off and landing. CMAPS uses a network of sensors to detect and verify the launch of shoulder-fired missiles and tracks those missiles with great precision. High-power infrared countermeasures are then directed to the missile, breaking the missile's lock on the aircraft. CMAPS can protect against multiple threats, be rapidly deployed to any airfield, and operate safely in both forward deployed and urban areas.

Table 25. Examples of some ground-based CM systems.

2. Airborne-based Solutions

Today, network-centric warfare has become an important task. When one aircraft detects a missile launch, this information can be sent to all other nodes, i.e., aircraft. The standoff aircraft carrying out their EW mission and other close-in aircraft, e.g., UAVs, can share this information. The position of the threat launch information can be automatically sent to the nearest ground security forces. This solution can be combined with other military operations.

As a part of Project Chole, there are some tests ongoing to detect and jam missiles using a high-altitude UAV patrolling 60,000 feet above the airport in order to protect aircraft taking off and landing.[72]

F. CONCLUSION

A single solution for defeating the threat is far away. Therefore, expendables, suppression techniques, and onboard jammers should continue to be used for all types of threats. In the past, chaff, flares, or jamming systems were under crew control and used manually. Now the management of these systems requires a dedicated computer to coordinate all required efforts. as

[72] Doyle, 2008.

shown in Figure 66. Using onboard and off-board systems coherently enables better susceptibility reduction. Onboard systems can degrade acquisition, target tracking, and missile guidance functions. Off-board systems are used in the later stages, in the endgame, to decoy the missile from its target.

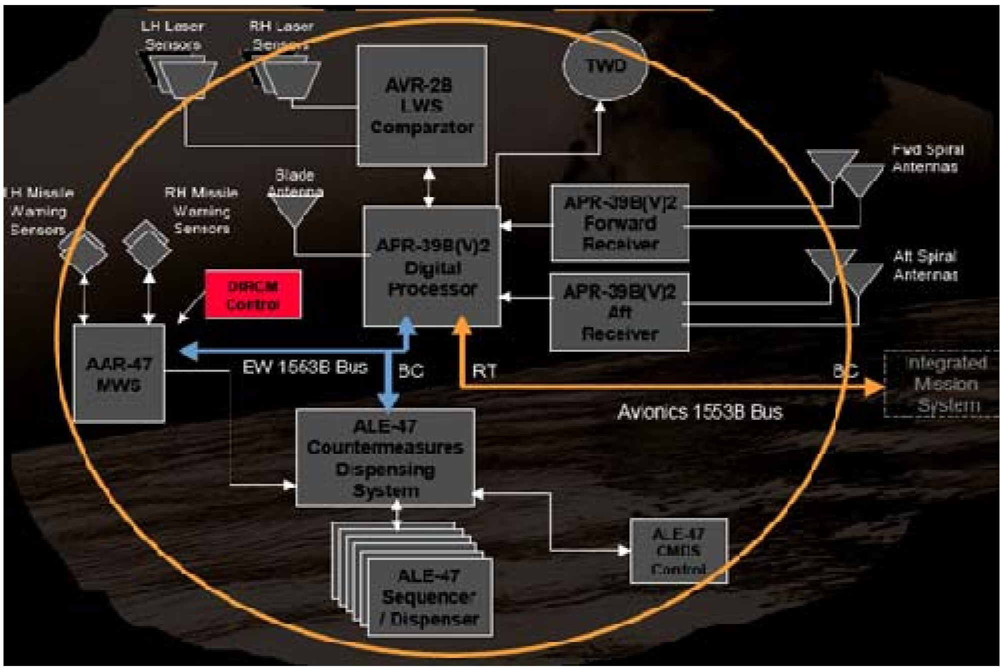

Figure 66. PMA272.[73]

To form a suite for aircraft protection the needs are more power, more antennas, more sensors, and more expendables.

[73] ATRB, PMA-272's EW open architecture roadmap, 2007, 2.

VI. AIRCRAFT SURVIVABILITY AGAINST THE SAM THREAT

Military aircraft are not built to fly in only normal situations. In a hostile environment, there are natural and man-made problems that the aircraft has to deal with to survive. If the aircraft sustains severe damage and can still fly, it is a survivable aircraft.

A. DEFINITIONS

"Susceptibility: The inability of an aircraft to avoid being hit by the hostile environment."[74] Susceptibility is related to a missile's capability to hit the aircraft. i.e., an aircraft's lack of capability to divert the missile and atmospheric conditions in which the missile and its guidance are affected. Following an aircraft until it is hit is the most important function of the missile. However, in the end, the aim of the missile is to shoot down the aircraft by giving damage. So its warhead and fusing system must have a capability to do so. In this point of view, aircraft vulnerability has a meaning. "Vulnerability: The inability of an aircraft to withstand the damage caused by the hostile environment."[75] The aircraft should bear all damages to survive.

The steps of fight between an aircraft and a missile happen based on probabilities. In the steps below, everything is thought positive on the missile's side:

Acquisition: Air defense is ready at the battlespace, either alone or part of an integrated defense system, which communicates and exchanges information about the battlespace picture. The threat is ready to search for aircraft visually, by RF, by IR, or by other means.

74 Ball, 445.

75 Ibid., 603.

- Detection: Threat detects and acquires contact.
- Launch: The threat identifies the contacts visually or via electronic interrogation, tracks a hostile target, prioritize the targets, and fires a missile.
- Intercept: Fly the projectile to meet with the target.
- Hit/Fuze: Hit the target or detonate the HE warhead by proximity fusing.
- Kill the target or the target survives.

So each step may also have a negative probability, as shown in Figure 67. The desired aim for the aircraft's survivability is to break this chain in earlier stages. In other words, it must defeat the threat as early as possible because as the missile goes forward through the steps positively, it prevents the aircraft from conducting its own mission either by killing the aircraft or with some virtual attritions. Threats are on the scene to shoot down the aircraft and, if not, to degrade the offensive accomplishments of the aircraft against the platform that is protected. For example, a bomber aircraft bombing from a higher altitude increases its survivability but also decreases its offensive capability. Therefore, air defense reaches a virtual attrition.

When aircraft are forced to accomplish their missions at higher altitudes, the accuracy of the mission is degraded. Flying nap-of-the-earth makes it harder for ground-based weapons system to acquire the aircraft. However, they are more susceptible to intense small-arms fire.

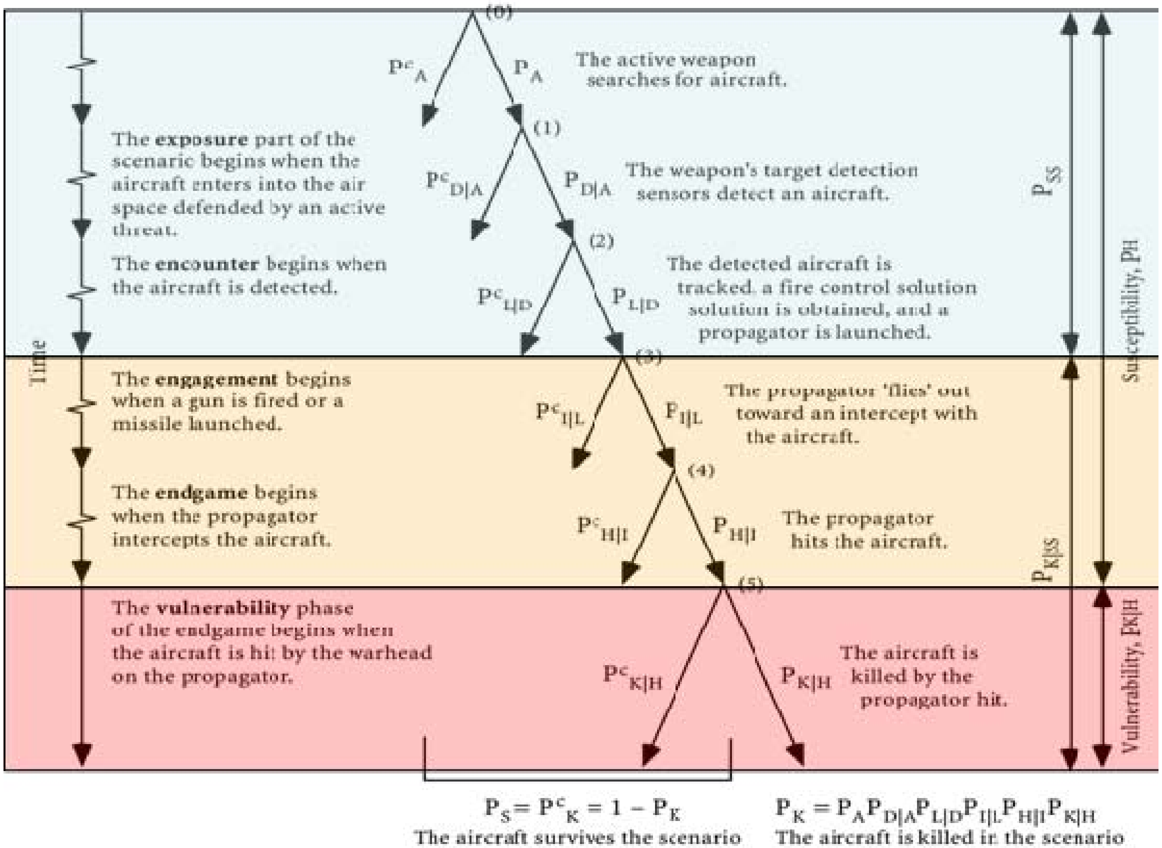

Figure 67. Encounter between an aircraft and a weapon.[76]

Aircraft may not survive if one of four essential functions (lift, thrust, control, and structural integrity) fails. Those are the vital functions that must be kept safe by preventing a hit on wings, tail, aerodynamics, engine, aircraft control rods, surfaces and critical system components.

If an aircraft is hit by a missile and withstands the damage, it becomes more susceptible to other shots originating from different weapons in the battlespace. The occurrence of one event might be affected by another event. If the aircraft's engine is damaged by a hit, its speed and maneuverability decreases remarkably. It becomes more susceptible to further shots.

[76] Ball, 11.

Survivability must be considered from the early design stages. Otherwise, it becomes more expensive and much more difficult to apply later. Survivability can be gained by a good design. Survivability should be thought of from the very beginning of the design.

Implementing survivability enhancement features is difficult and expensive; however, they pay off by increasing the combat cost effectiveness. An aircraft should be able to complete its mission with some damage. This plays an important role. Another aircraft does not need to be sent and time is not lost. The asset is not lost. When it comes back with or without damage, then it can be sent quickly on another mission.

Threat characteristics are threat types, warhead, and damage mechanism.

The lethality of short-range missiles is affected by the distance at which the missile operator launches the missile. If the contact fuze missile is fired too early and the missile propellant burns out before it hit the target, it may not do much damage since it has low kinetic energy. If the missile’s shelf life has expired, then either the fuze or the warhead may not initiate the explosion.

SAM damage can be reduced by early damage detection, classification, regaining the control of aircraft by reconfiguration, and use of different engine power adjustments to have an adaptive control.

Some of the questions for assessment of survivability are:

- How can susceptibility be reduced?
- What is the vulnerability of large aircraft to SAMs?
- Under an attack, which part can be hit?
- How much damage can the aircraft tolerate?

B. TESTING

1. Simulations

Open-loop simulations: human effects are in the loop.

Closed-loop simulations: human effects are not involved in this simulation. Several thousands of simulations can be run for statistical purposes and, obviously, they are faster than real time.

2. Live-fire Testing

Large aircraft vulnerabilities have been studied by the Large Aircraft Survivability Initiative (LASI). In these tests, pylons, wings, empennage, and fuselage are hit by missiles.[77] Damage size and fire causes are the most important things that were researched. To defend the aircraft, the threat must be prevented from the very beginning to the very end of scenarioby preventing the missile from being launched, preventing a hit, and preventing a kill.

Figure 68. IR live-fire test.[78]

[77] Czamecki, 2005, 10.

[78] Ball, 171.

3. Recent Examples

An Airbus, owned by European Air Transport and operated on behalf of DHL, was hit by an SA-14 SAM while climbing through 8000 feet shortly after departure from Baghdad. The missile struck the wing and penetrated the No. 1A fuel tank. Fuel ignited, burning away a large portion of the wing. To make things worse, the plane lost all three hydraulic systems and the pilots had to attempt a landing back at the Baghdad airport. After a missed approach, they were forced to circle the field until they finally landed heavily on runway 33L, 16 minutes later.

Figure 69. DHL aircraft was hit by MANPADs.[79]

Although a C-17 is equipped with self-defense systems, in December 2003, a C-17's left engine was hit by a MANPAD and caught fire. The plane landed safely back at the Baghdad airport.

As part of the US/UK war with Iraq, missiles were fired on the Al Taqqadum military airport. On 4 April 2003, an Ilyushin IL-76 was reported damaged beyond repair.

On 28 November 2002, in Kenya, an Israeli Boeing 757-300, after takeoff and passing 500 feet above ground level (AGL), experienced a "bump" then very

79 Air Disaster, "Accident Photo: DHL A300 OO-DLL - Baghdad, Iraq," http://www.airdisaster.com/photos/oo-dll/3.shtml (accessed 20 March 2008).

shortly saw two smoke plumes. The two missiles missed the aircraft because the terrorists launched the missiles too early; the missiles need 800 feet AGL to track the target.

An RAF Hercules, XV179, departed Baghdad for a routine flight to Balad. The airplane was flying at a low level when it was hit by enemy fire. The outboard 23 feet of the right wing separated and the Hercules lost control. It crashed and broke up.

On 11 September 2004, the No. 1 engine of a C-17 was struck by ground fire shortly after takeoff.

In January 2004, the No. 4 engine of a C-5 was reportedly hit by a surface-to-air missile. The crew reported excessive engine vibrations and declared an emergency. The plane returned to the airport and landed safely.

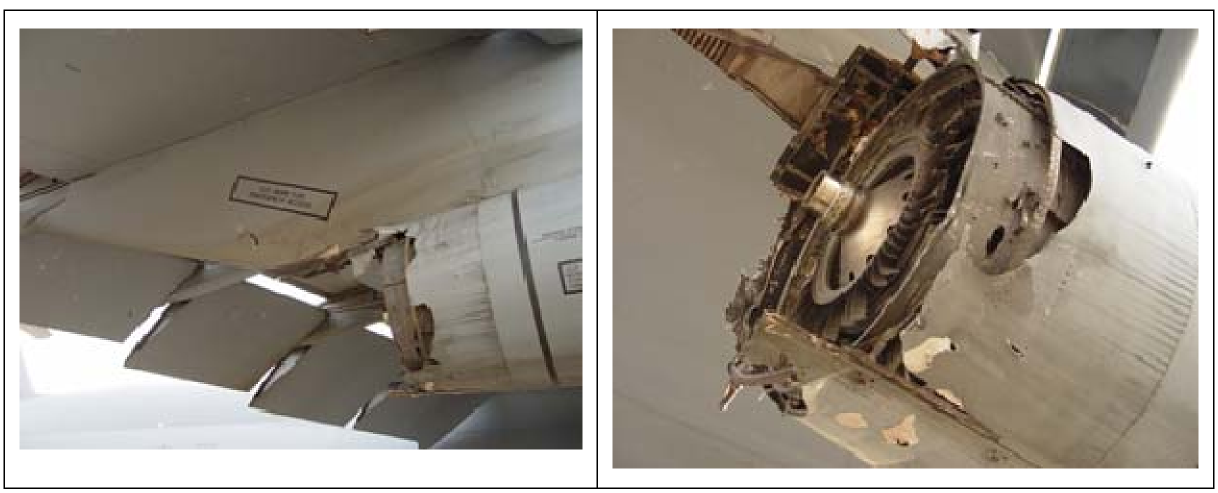

Figure 70. A C-5 was hit by MANPADs.[80]

[80] ASN Aircraft Accident, "Lockheed C-5B Galaxy," http://aviation-safety.net/database/record.php?id=20040108-0 (accessed 20 March 2008).

Date	Missile type	Aircraft type	Notes
02Jan99	Unknown	C-130	UN plane shot down in central Angola
26Dec98	Unknown	C-130	UN plane shot down in central Angola
10Oct98	SA-7	Boeing 727	Airplane struck over DR of Congo.
15Dec98	Unknown	An-12	An-12 struck by a missile enroute to Luanda.

Table 26. Some other examples against large aircraft.[81]

[81] James C. Whitmire, “Shoulder Launched Missiles (a,k.a.MANPADS),” 2006, http://www.stormingmedia.us/43/4351/A435164.html (accessed 11 January 2008).

VII. CONCLUSION

A. GENERAL REVIEW

It seems like there is a countermeasure for every weapon developed. Electronic warfare presents a step-by-step sequence of events. Do not be detected. Nevertheless, if you are detected, then do not be acquired. Moreover, if you are acquired, then do not be tracked. However, if you are tracked, then do not let the missile launch. Nevertheless, if the missile is launched, then don’t let the missile hit the aircraft. However, if the missile does hit the aircraft, then find a way to survive and land the aircraft safely.

Digital technology makes devices smaller, lighter, cheaper, more powerful and more integrated. This leads to more lethal weapons and countermeasures. This study focuses on the SAM threat. A SAM launcher can be a node within a large-scale integrated air defense system or an individual MANPAD surprisingly appearing in an unexpected time and place. Operation Iraqi Freedom shows that MANPADs, RPGs and small-arms fire are very effective against slow-flying helicopters and aircraft.

From the missile operator’s point of view, sometimes they are not sure if their target is actually an enemy. Therefore, many times operators face critical decisions to shoot or not, since it is hard to establish and radiate the actual electronic order of battle to all allied units in the battlespace. Misuse or problems with the programs may end with rare incidents of fratricide. Those problems can originate from a frequency mismatch, interference, system error, operator error, or misclassification. In order to eliminate operator errors, the speed and altitude of the target must be considered.

The lifespan of a large aircraft is around 50 years. They must survive to remain in service that long. Large aircraft have large vulnerable areas. They are slow and not agile. They operate at different altitudes. Flying low makes them

even more vulnerable. As the vulnerable area of the aircraft increases, the probability of a hit increases. Armor and redundant systems may decrease the vulnerability of the aircraft.

The ability to detect a threat is the one of the important tasks for countering. Threat warning systems can identify and prioritize the threats. The sensor must be located so that it can cover 360 degrees.

Today, to counter a threat, an aircraft must have onboard or off-board countermeasures that use the RF, IR or laser portion of the EM spectrum. This situation leads to different distributed components and systems, which means extra weight and specialized maintenance personnel.

A typical EW suite is composed of an EW management system, a missile warning system, RF electronic countermeasures, directional infrared countermeasures, countermeasures dispenser systems, a laser warning receiver, and the cockpit display. All aspects of these systems must be integrated to ensure maximum effectiveness. Logistics, training, operating environment, and system reliability should all be identified. To be one step ahead of the threat, the self-protection suite should be easily updated both in means of hardware and software. The suite should provide operational flexibility and interoperability.

The EW suite can work against current and future threats as well as older threats. As times goes by, more agile and capable threats will be seen. Reducing susceptibility will always be a problem for large aircraft. As technology develops and the components of electronic devices become smaller, threats will proliferate more easily. As we saw in the latest examples in Iraq, MANPADs can be easily distributed to terrorists when the security of a country decreases. Therefore, aircrew and mission planners must know the basics of the technology that they use.

B. WHAT KIND OF SELF-PROTECTION SUITE?

1. Solutions

Single solutions are still far from defeating the threat. Therefore, for all types of threats, expendables, suppression techniques, and onboard jammers should be coordinated. Countering the threat in the early stages must be the first aim of a self-protection suite.

For threat warning, a digital RWR, an IR-based MAWS, and an LWR should be employed. The digital RWR must be capable of detecting LPI radars. An IR-based MAWS gives better angle-of-arrival information and is also usable after the burnout phase of the missile. LWR can alert the crew to the presence of laser-guided weapons. Integrating the IR-based MAWS and the LWR may prove effective.

For countering threats, it may be utopian to think that only one HPM can defeat all kinds of missiles for the time being. For large aircraft, it will be employed in the near future. For now, directed IRCM can provide enough power to defeat IR missiles and RFCM and towed decoys can more effectively counter missiles that employ even monopulse seekers. Dispensers and expendables are indispensible for endgame scenarios and for backup. An integrated EW cockpit display unit and a dedicated computer for managing self-protection give the best reactions against threats.

The system must be lightweight, low drag, upgradable, reprogrammable, affordable, and have a low cost of maintainability and training.

2. Future Threats

In an otherwise low-threat environment, the biggest threat in terrorists' hands is first- and second-generation missile technology. Eventually, they will have newer technologies and we must keep up with them and even use further developed countermeasures to be one step ahead. These are individual systems

and one cannot easily guess where they will show up. Multispectral multimode seekers discriminate the target signature. Low-observable missile plumes, RCS, and IR signature are used to avoid being detected and are becoming more lethal.

In a high-threat environment, where more sophisticated and integrated systems are used, the threat moves to RF-based systems. They mostly have longer ranges, all-weather capabilities, and stationed systems.

A combination of guidance systems makes it harder to defeat the threat. Multiple sensor-employed missiles will become more common in the future.

Laser beams will be used to blind crew members unless laser-resistant goggles are used.

Various types of self-defense suites are shown on the basis of aircraft platforms below. As the value of the aircraft and the importance of its mission increases, more countermeasure systems are added.

3. Balanced Solution

Every new system on an aircraft solves one or more problems; however; they also bring new burdens with them. The self-protection suite occupies space and adds extra weight, maintenance, and upgrade problems. A balanced solution must comprise low weight, low drag, minimal false alarms, long maintenance time between failure times, low maintenance time, and easy upgrades. Since the life span of a large aircraft is 50 years, it goes through some renovation over time. “Plug-and-play” systems enable easy integration. It also allows operators to add sensors easily or upgrade existing components in response to budgetary increases and/or changes in the threat environment. The impacts of structure, drag, weight, and electrical power requirements must be thought out before initiating countermeasures placement.

To modify a C-5 with a self-protection suite costs approximately one million dollars.[82] But the loss of a large aircraft has many economic and psychological effects on both military and civil aviation. On the other hand, the damage caused by MANPADs in recent incidents show that IR seekers fly directly to the engine and the damage is limited to the engine. Where the missile strikes the aircraft and the size of the warhead are important factors.

- What a pilot needs

Aircrews need situational awareness, a digital map, and indications of the threats noted. They do not like the extra workload while executing an operation. EW suites must be easy to operate and should require little training time.

- What an air force needs

An air force needs current data so all the aircraft flying can see the same situational picture. There should be a low-cost, two-way data link between the aircraft and the command center.

- What maintenance personnel need

Plug-and-play systems that come with a long time between maintenance intervals and do not give any extra workload to the aircrew. There can be a dedicated self-defense computer that integrates warning systems with automatic countermeasures systems.

It seems like it is not worth equipping aircraft with an EW suite in peacetime. However, it pays off in war. Large aircraft are made not only to fulfill the requirements for peacetime but also wartime. To complete a mission and to be ready for further missions, the susceptibility of aircraft must be decreased, in other words it should not get hit. If hit, it must withstand the damage to complete the mission and return to base. In order to have this survivability feature, it must employ an appropriate design according to the aircraft’s type.

Further studies may include developing survivability guidelines for different types of aircraft.

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[82] Thomas Freese, Force protection and strategic air mobility, 6.

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